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Science and Engineering**

Recommendations for Evaluating Multiple Filters in Ballast Water Management Systems for US Type Approval

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EXECUTIVE SUMMARY

International, national, and regional efforts have been initiated to address the introduction of aquatic nuisance species (ANS) from commercial ships' ballast water and sediment. To meet these stringent discharge standards, most vessels will install a ballast water management system (BWMS). Of the BWMS currently installed on vessels, or those in development, most treat water using a combination of physical separation (usually filtration) followed by a disinfection step (e.g., electrochlorination or ultraviolet [UV] radiation). Further, some BWMS manufacturers specify multiple filtration system options to accommodate different flow ranges or allow filters to be sourced from multiple vendors (thus reducing the risk associated with maintaining a single source of supply). Each filter may, however, affect performance of the downstream treatment—or the overall system—in a different way. This report provides guidance to the US Coast Guard (USCG) as they consider type approval (TA) applications for BWMS that specify the use of multiple filters.

To address this goal, reports from manufacturers were reviewed, the published literature was summarized, and filter manufacturers were contacted. Using filters to manage ballast water is both a new application and an emerging market, so it is no surprise that standards relevant to this application still need to be developed. In BWMS, filters are often specified with a nominal pore size in the range from ≥10 µm and <50 µm. Filter efficiency is often unspecified, but filters in most applications are evaluated by log reduction or percent removal. **In this search, no standard was found that quantified removal by the *absolute number* of particles passing through the filter.** This point is important, as the international and US discharge standards are numeric standards. While some standards provide a challenge consisting of a single organism or solids loading, none specifies an assemblage of organisms representative of organisms typically found in harbors or a suite of variable-sized and malleable particles that could simulate organisms in aquatic communities. Developing a comparison metric, such as the beta ratio or minimum efficiency reporting value (MERV) rating used in other industries, would be exceptionally useful for stakeholders that might want to interchange different ballast water filters in BWMS, because it would accurately compare filters without having to rely only on the nominal rating as currently supplied by vendors of filter systems.

Regarding a means to assess BWMS with multiple filters, three options are presented here. The most highly recommended option is to maintain the default approach wherein each BWMS undergoes TA testing with a single filter, and if an additional filter is specified, an additional full complement of land-based, shipboard, operations and maintenance (O&M), and component tests would be conducted to obtain TA for the new configuration. This approach would lend the most confidence in using the alternate filter, but it requires a substantive investment of time and money to complete requisite testing, and this is extremely unlikely to be practicable.

A second approach is to conduct a full suite of TA testing on a BWMS with a "base filter" configuration. Then, a two- part approach would be followed: (1) A design study would be conducted, and (2) A reduced number of BE tests of the alternate filter as installed in the BWMS would be conducted at a USCG-approved independent laboratory (IL). This effort, however,

would be reduced relative to that of full TA testing. Here, three land-based tests would be conducted, and O&M and component testing would also occur.

If time or practicality does not allow the above scenarios to be implemented, a third option is available, although it is not recommended at this time. In this case, a design study would be completed, and it would be followed by testing to demonstrate equivalence of an alternate filter with the original filter. Here, a series of land-based performance tests would be conducted on the filter itself (not installed in the BWMS). Such performance testing would require the same rigor as US TA testing with respect to the quality assurance, testing protocol, and data reporting. A test protocol would be developed following a process similar to that used for the Environmental Technology Verification (ETV) Program Protocol for land-based and shipboard testing of BWMS, that is, by convening panels of experts. This approach could be shown to be as effective as the first two approaches, so it should be pursued.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Term	Definition
AMS	Alternative management system
ANS	Aquatic nusiance species
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASTM	ASTM International
β	Beta ratio
BWMS	Ballast water management system
CDF	Cumulative distribution function
CFD	Computational fluid dynamics
cfu	Colony forming unit
CFR	Code of Federal Regulations
COTS	Commercially-available-off-the-shelf
DHI	Danish Hydrological Institute
DNV-GL	Det Norske Veritas Germanischer Lloyd
DOP	Dioctyl phthalate
EN	European standards
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
FNU	Formazin nephelometric unit
G8	International Maritime Organization Guidelines for Approval of Ballast Water Management Systems (G8)
GF/C	Glass microfiber filter (Coarse)
GF/F	Glass microfiber filter (Fine)
GSI	Great Ships Initiative
h	Hour
IL	Independent Laboratory
IMO	International Maritime Organization
ISO	International Organization for Standardization

Term	Definition
L	Liter
m^3	Cubic meter
MERV	Minimum efficiency reporting value
mg	Milligram
mL	Milliliter
MEPC	Marine Environment Protection Committee (of the International Maritime Organization)
MERC	Maritime Environmental Resource Center
MM	Mineral matter
M/V	Motor vessel
MEA	Marine Eco Analytics
NIOZ	Royal Netherlands Institute for Sea Research
NIST	National Institutes of Standards and Technology
NIVA	Norwegian Institute of Water Research
NRL	United States Naval Research Laboratory
PMF	Probability mass function
POC	Particulate organic carbon
O&M	Operations and maintenance
ppm	Parts per million
PSD	Particle size distribution
psu	Practical salinity units
SAE	Society of Automotive Engineers
SDI	Silt density index
SOP	Standard operating procedure
STEP	Shipboard Technology Evaluation Program
STO	Standard test organism
TA	Type approval
TF	Test facility
TQAP	Test quality assurance plan

Term	Definition
TRC	Treatment rated capacity
TSS	Total suspended solids
USCG	United States Coast Guard
UV	Ultraviolet
WET	Whole effluent toxicity
°C	Degrees Celsius
µm	Micrometer

1 INTRODUCTION

International, national, and regional efforts have been initiated to address the introduction of aquatic nuisance species (ANS) from commercial ships' ballast water and sediment discharges. The International Maritime Organization (IMO) adopted an international convention (IMO 2004), which remains to be ratified sufficiently to enter into force. In the US, several legislative and executive actions governing ballast water discharges were promulgated by the US Coast Guard (USCG) and the Environmental Protection Agency (EPA) between 1990 and 2012 (e.g., USCG 2012, EPA 2013). Both the IMO and US actions aim to limit the number of living organisms discharged in ballast water by establishing a discharge standard allowing: (1) <10 organisms ≥ 50 µm in size (typically dominated by zooplankton) per m^3, (2) <10 organisms ≥ 10 µm and <50 µm in size (typically dominated by protists, often phytoplankton) per mL, and (3) limits on indicator and pathogenic bacteria per 100 mL (<250 colony forming units [cfu] of *Escherichia coli*, <100 cfu of intestinal enterococci, and <1 cfu of toxigenic *Vibrio cholerae*).

To meet these stringent discharge standards, most vessels will install a "ballast water management system" (BWMS). Of the BWMS currently installed on vessels, or those in development, most treat water using a combination of physical separation (usually filtration) followed by a disinfection step (e.g., electrochlorination or ultraviolet [UV] radiation). Prior to obtaining flag state Type Approval (TA) for installation aboard vessels, BWMS must undergo land-based and shipboard verification testing to determine their efficacy in removing or killing living organisms.

In the US, the requirements for US TA application and verification testing are codified in the US Code of Federal Regulations (CFR, 46 CFR 162.060). Testing and test documentation must be in accordance with regulatory references for quality management (International Organization for Standardization, ISO 17025:2005) and will proceed following the "Generic Protocol for the Verification of Ballast Water Treatment Technology" (hereafter, "ETV Protocol"; EPA 2010), which was incorporated by reference into the USCG final rule on ballast water. The Protocol was developed under the Environmental Technology Verification (ETV) Program in a joint effort between the USCG and the EPA. Accordingly, TAs will be granted only for BWMS to operate within the parameters under which they have been tested (e.g., under specific salinity ranges). In addition to land-based and shipboard verification testing under well-documented biological and water quality conditions, USCG regulations require assessments of all components, marine safety, and manufacturing processes.

To date, all BWMS that have received TA have achieved it following the IMO process, in particular, using testing parameters outlined in the IMO Guidelines for Approval of Ballast Water Management Systems (G8 guidelines; IMO 2005). The G8 guidelines provide a general framework for conducting both land-based and shipboard TA testing, but they do not provide specific protocols. The US regulations, on the other hand, identify specific test procedures and methods by referencing the ETV Protocol, including challenge requirements for land-based testing. Additionally, testing must be performed by a USCG-approved Independent Laboratory (ILs).

Systems that have obtained a TA from a non-US administration may request a USCG determination as an Alternative Management System (AMS). An AMS acceptance allows the interim use of a BWMS (for up to five years after the vessel is required to comply with US discharge regulations); during this time, it is expected that the BWMS will undergo TA testing according to the US standards (i.e., following the US regulations and, by extension, the ETV Protocol). Either a BWMS vendor or an IL may submit an AMS application to the USCG, but it is necessary that an application for TA be submitted to the USCG concurrently. While this application will not result in US TA, it is submitted with the aim of identifying gaps in existing foreign TA data packages—in this manner, it is analogous to a preliminary TA application—so gaps identified by USCG can be addressed through additional testing before a US TA application is submitted.

1.1 The Use of Filters in Ballast Water Management Systems

A filter system (filter) is often included as the initial treatment step in a BWMS. Not surprisingly, many commercial filtration technologies are available to filter ballast water. Some BWMS manufacturers specify multiple options for their filtration systems to accommodate different flow ranges or allow filters to be sourced from different vendors (thus reducing the risk associated with maintaining a single source of supply).

If performance specifications are equivalent, then different filter types should remove particles with the same efficiency. However, in practice, different filters show a diverse range of design and operation (e.g., filter types include disk filters, filter bags, cartridges, and screens); each filter type may demonstrate different effectiveness in ballast water applications. These difference stem from variations in the pore shape (square, diamond, rectangle, circle, or other), the spacing of pores, and the manufacturing process of the filter element. Additionally, some filters operate on the principle of surface filtration (in a single layer), and some operate using depth filtration (multiple layers), which can influence particle retention. Soft-bodied plankton with dimensions close to the filter's rated pore size are difficult to retain on all filter types, but some pore shapes may perform better than others. Finally, filter-cleaning methods may also affect the efficacy of the filter. A heavily loaded filter may be more effective at filtering smaller particles, but at the expense of reducing volumetric flow and increasing pressure differentials.

While a BWMS vendor may consider a range of filter types and filter manufacturers to be equivalent or interchangeable, differences among the filters may affect the performance of the entire system. To assess the effect of multiple filter types, one approach is to have the different filters validated independently of the overall BWMS. This practice would require a new, validated protocol to be developed to ensure all filters are evaluated equivalently to meet vendor claims for operational performance and biological efficacy (BE, for organism removal). This task would be no small feat: the ETV Protocol was developed, tested, and finalized over 10 years.

In fact, TA testing of BWMS in the US is required to examine performance of the *complete* BWMS, following the US regulations "…The BWMS includes all ballast water treatment equipment and associated control and monitoring equipment" (USCG 2012). Thus, the regulation could be interpreted to mean a complete suite of full-scale, land-based, and shipboard

verification testing of the BWMS should be conducted for each filter configuration. Some BWMS identify the use of multiple filters on their TA certificates, but other components, such as UV reactors, might also be designated to have additional, “alternate” configurations or suppliers. Thus, it is possible to envision a large matrix of testing for each of the scenarios. The practicability of requiring a full suite of land-based and shipboard verification tests for every different configuration of the BWMS seems not practicable.

1.2 Goals and Objectives

The ANS research group at the US Naval Research Laboratory (NRL) was tasked by the USCG to develop a process for evaluating TA applications that specify multiple filters (i.e., a BWMS with an original filter used in TA testing and at least one other, alternate filter). For the purpose of this report, an alternate filter differs from the original filter because it is (1) Manufactured by a different vendor or (2) Has a different configuration (e.g., type of filter or pore size). As part of this tasking, several technical data packages accompanying AMS applications were examined to determine where multiple filters were used and how they were evaluated by the BWMS manufacturer. Notably, an intent of TA testing is to assess the consistency of the *system* performance, and that caveat needs to be considered if only a *component* (here, a filter) is tested. Thus, both system and component testing are discussed in this report. Further, this report assesses alternate filters by reviewing reports from manufacturers, summarizing the published literature, and communicating with filter manufacturers. The objectives of this assignment were to contact filter manufacturers to determine their internal testing processes, review test procedures for determining filter efficiency reported in AMS applications, and make recommendations for testing and future steps. Finally, the possibility of establishing equivalency among components without undergoing a full complement of TA testing is considered.

2 RELEVANT TERMS

When filters and their associated efficiencies are discussed, a number of parameters are important to consider. These terms are used throughout the report and are defined here for clarity (Table 1). Filters used in BWMS often have parameters listed in product marketing brochures; these parameters include ranges of potential flow rate, design pressures, materials, and micron ratings (nominal pore size). Items from Table 1 that are *not* commonly provided in brochures include absolute pore size, effective filter area, filtration velocity, flux, porosity, or throughput.

Table 1. Definitions of terms relevant to filter testing.

Term	Discussion
Absolute pore size	Pore size based on empirical measurements of the pores in the filter
Differential pressure (Δp or DP)	The diffence in water pressure as measured at the inlet and outlet of the filter; in BMWS, the differential pressure increases as the filter starts to clog
Filter area or Effective surface area	Filter area available for filtration; this area calculation should subtract any solid barrier that obstructs fluid flow or particle separation
Filtration Velocity	Flow rate per area of effective filtration area; in the metric system, this parameter may be expressed as meters per hour ($m\ h^{-1}$) ($m^3\ h^{-1}\ m^{-2} = m\ h^{-1}$)
Flux	In membrane filters, this is defined as the throughput of a pressure-driven membrane filtration system, which is expressed as flow per unit of effective open membrane area; this term is not commonly used in BWMS filters, but for purposes of this paper, it may be defined as flow per unit of effective filter area
Nominal pore size	Pore size based on the size of the particles retained by the filter
Porosity	Often called filter open surface area; this is the ratio of all the pores in a material to the volume of the whole
Throughput	Volume of fluid able to pass through a filter prior to filter clogging or plugging

3 TYPES OF FILTERS USED IN BALLAST WATER MANAGEMENT SYSTEMS

Filters are designed to remove materials, such as particles or organisms, from flowing fluids, including water, oil, or air. Assessing and rating a filter depends on how and where it is used, along with its operational environment (flow and pressure requirements). A variety of parameters is examined to establish filter performance; a summary of commonly used rating systems and tests is provided in Appendix A. While considering such tests, this report focuses primarily on tests and standards applicable to filters used in BWMS.

Filters used as pretreatment (i.e., the first stage) of a BWMS are typically designed to remove the larger size class of organisms and organic particles ($\geq$50 µm) to reduce downstream treatment dose and contact time, as larger organisms can significantly increase treatment requirements. A filter can provide the added benefit of reducing sediment, which can interfere with treatment (e.g., by reducing optical transmission in UV treatment), and when used on uptake, filters reduce particulates that settle and accumulate in ballast tanks, adding weight and providing habitat for benthic organisms. Filters for ballast water treatment are commonly rated with a nominal pore size in the range $\geq$10 µm and <50 µm. While pore size is a nominal dimension for specifying the

rating of a filter, it is not an absolute number. Retention of particles by the filter depends on a number of factors, including the characteristics of the particulates (e.g., particle size, shape, and malleability) and the operational parameters (e.g., flow rates, flushing intervals, and pressure differentials). In particular, organisms may have complex shapes, soft or hard bodies, or protruding appendages; they may also change shape depending on life stage. All of these factors can influence the effectiveness of the filter in removing certain organisms. Thus, specifying a nominal particle size does not guarantee removal of a given organism or a given particle size.

3.1 Filter Approaches

Typically, filters used in BWMS create a barrier where large particles or organisms are stopped, and water and smaller particles are allowed to pass through. Virtually all filters used in BWMS employ an automated, self-cleaning design that allows some degree of filtration, even during cleaning cycles. Typically, filters operate during the ballasting (i.e., the uptake) cycle of a BWMS. As water passes through the filter, the filter media traps particles larger than the rated size of the filter, and the filtrate is passed on to the downstream process (e.g., disinfection). Some systems use a self-cleaning approach, and some use replaceable cartridges. Periodic cleaning cycles remove the trapped particles from the media so the filter does not clog. The water used for cleaning (also known as backflushing) is typically returned to the uptake water source. Other types of filters such as disc, cartridge, and membrane, are also used in ballast water.

3.1.1 Screen

Screen filters are typically cylinder-shaped filters that are placed into a filter housing, and they filter water that crosses the filter surface. The screen of a filter is typically formed from layers of woven metal mesh (described below). They usually operate with water flowing from the inside of the screen to the outside, so particles are trapped on the interior surface of the screen. When the filter clogs or reaches a pressure differential set point across the filter, a cleaning operation is initiated. The most common cleaning operations are referred to as backflush or suction cleaning. Backflush cleaning reverses the water flow through the filters to dislodge particles from the interior of the screen. The particle-laden discharge water flows back to the source. Suction cleaning filters have a mechanical cleaning system that moves along the interior of the screen during backflush. A negative pressure differential is created at the inlet of the suction cleaning system that causes water and particles to flow in reverse to clean the screen. The suction cleaning system cleans a small percentage of the available filter area at once, so the overall flow through the filter can be maintained.

3.1.2 Candle

Unlike screen filters with a single surface, candle filters use several small candles (filters) that operate in parallel within a single housing. Two shapes were encountered during this review: conical and cylindrical. The candles are often built using metal woven elements described below. When the candle filter operates, water flows from both ends of the candles, and the filter captures particles on the inside of the candle. Often, the differential pressure across the filter housing is monitored, and when it reaches a set point, the cleaning operation is started. Generally, candle filters have a cleaning mechanism referred to as a flushing arm or flushing

connection. Candles typically are cleaned individually or in pairs by moving the flushing arm to the individual filter element (candle). The flushing arm stops the water flow into the candle and then opens a backflush valve at atmospheric pressure, or to a backflush pump. The resulting differential pressure reverses water flow through the candle, removing material accumulated on the filter surface.

3.1.3 Stacked disc

Stacked disc filters use discs that have diagonal grooves on top and bottom that are cut to a specific micron size. The discs, often a polypropylene material, are stacked in a column and compressed to create an opening rated for the size of particles to be removed by the filter. While filtering, water flows from the outside of the disc inward toward the center. The diagonal grooves for each disc run opposite the groove below or above it, and create a set of openings that trap particles in depth filtration rather than surface filtration. Several columns of discs are placed in parallel within a single filter housing. A manifold of filter housings is set up in parallel to achieve the water flow requirements for the application. Differential pressure is measured across the entire filter manifold, and when it reaches a set point, a backflush operation is initiated. Generally, the column of stacked discs within a single housing is uncompressed, and water flow through the disc filter is reversed, which cleans the particles from the discs. The entire manifold of filter housings is cleaned sequentially by backflushing.

3.1.4 Membrane

At the time of this review, only one system—Mitsui Engineering and Shipbuilding's FineBallast™ MF—was encountered that specifies a membrane filter (MES 2014). This system is unique in that is uses only filtration and does not require a downstream disinfection step. The system uses a two-step filtration process in which a pre-filter removes particles ≥100 µm. Next, a membrane filter removes the remaining particles, although the characteristics of this filter stage were specified in neither the product documentation nor the relevant TA certificate. Typically, membrane filters achieve pore sizes in the micron to submicron range. The membrane filter is periodically cleaned by flushing to return filtered organisms back to the source. In addition, a clean-in-place unit provides additional cleaning of the membrane, using hydrogen peroxide. Presumably, this step occurs between ballasting operations. Any residual hydrogen peroxide is reduced to oxygen and water via a catalyst.

3.1.5 Hydrocyclone

Hydrocyclone filters are hydrodynamically designed to create centrifugal action to separate particles that are denser than water. Hydrocyclones do not provide a mechanical barrier to stop particles; rather, they rely on the centrifugal forces generated by cyclonic flow. Hydrocyclones have been used on BWMS, but not commonly, and these systems were not referenced in the AMS applications reviewed for this paper.

3.2 Filter Elements and Materials

Several types of filter elements and materials are employed in filtration systems used to process ballast water. The following sections provide examples of filter types often included in BWMS,

including wedge wire candle, wedge wire screen, weave wire candle, weave wire screen, plain weave, twilled weave, microfiber, stacked disc, single screen, and multiple screen (Figure 1 to Figure 5). This section illustrates the many ways ballast water filters are designed and configured to accomplish filtration.

3.2.1 Filter elements

Often, the name of the element refers to the method for constructing the element. For instance, a supplier of a woven mesh system may use power looms with high mechanical precision to weave a set of wires into a "weave wire" mesh. Different weaves are described below.

Wedge wire refers to the shape of the filter element. A wire with a "wedge" profile is welded to a support rod with a slot opening of a given size (e.g., 50 µm; Figure 1).

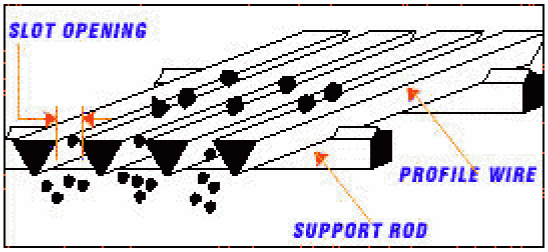

Figure 1. Wedge wire profile (Self cleaning filters 2014).

Weave wire refers to a filter layer that is created by weaving wires together to create the filter element (Figure 2). Often, the weave wire has additional layers to provide structural support.

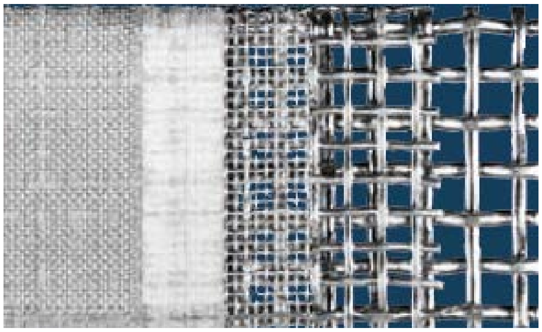
Figure 2. Weave wire profile (MossHydro 2014a).

Plain weave refers to a weave type in which every wire crosses alternately (Figure 3).

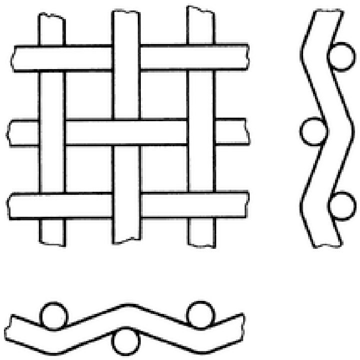
Figure 3. Plain weave wire (ISO 1990).

Twilled weave refers to a weave type in which two wires cross alternatively above and below two wires and vice versa (Figure 4); in the image at of the weave element, the 3rd vertical strand from the left matches the drawing at the right. Likewise, the 2nd horizontal strand from the bottom matches the image at the bottom).

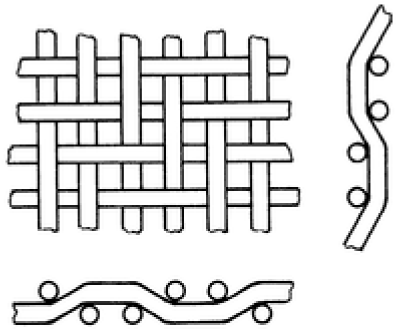

Figure 4. Twilled weave (ISO 1990).

Slotted element refers to a filter where slots are created in a tubular shape (Figure 5).

Figure 5. Slotted tube (HYDAC 2014).

3.2.2 Multi-layer Elements

Many of the filters reviewed in this report use a multiple layer system that incorporates one or more woven layers with structural reinforcement layers to provide strength. One supplier is Filtersafe®, which uses their “smartweave™” process to create a multiple layer mesh that has a top protective layer, filtration control layer with micron ratings between 15-500 µm, bottom protective layer, and reinforcement layer; these are sintered together in a cylinder. This filter is available in two types of stainless steel (316L and 904L Duplex) (Filtersafe® 2013).

3.2.3 Grooved Disc Filter element

Grooved disc filter elements use spiral grooves on each side to create minimum pore openings of a given size (e.g., 50 µm) to trap particles (Figure 6). Discs are held together by spring pressure during filter mode, and allowed to separate by backpressure in cleaning mode, which reverses flow to flush trapped particles from between the disks.

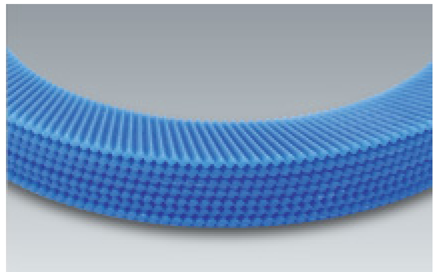

Figure 6. Disc filter element (Amiad Water Systems 2014).

3.2.4 Membrane

Membrane filters incorporate an engineered barrier that prevents particulate matter (including pathogens and organisms) >1 µm from passing (EPA 2005). The filter operates under a pressure- or vacuum-driven process to achieve separation. Membrane filters are commonly used in drinking water treatment, where performance is typically evaluated by measuring the log reduction of indicator organisms. Membrane filters are also used in the pharmaceutical industry for preparing sterile process water (McBurnie 2004).

4 AMS APPLICATIONS FOR BWMS USING MULTIPLE FILTERS

At the writing of this report, type approvals for BWMS have been granted only by non-US administrations, with testing conducted according to the IMO G8 guidelines (IMO 2005). Several manufacturers with foreign TA have pursued USCG AMS designations and have submitted TA data packages accompanying their AMS application. As part of the AMS acceptance process, data submissions were reviewed by the USCG Shipboard Technology Evaluation Program (STEP) team at the US Department of Transportation (DOT). In support of this report, the STEP team was asked to identify those applications whose TA specified more than one filter. Of 44 AMS applications received by USCG as of 31 OCT 2014, 12 (27%) identified two or more filter options during testing. The applicants and filters identified as either tested or included on the TA certificate are provided in Appendix B. Of these, 11 identified multiple filters on the TA certificate (OceanSaver listed only the FilterSafe® filter for TA). In addition, there was one filtration-only BWMS (Mitsui Fineballast™ MF) that specified two filters: the first filter (with Boll identified as the manufacturer; no alternate filter was specified), followed by a proprietary second filter (again, no alternate filter was identified). As no alternate filters were identified, this system was not reviewed for this study.

In total, six of these *systems* were reviewed. A seventh system, the Hyde Guardian system with Spin Klin filters, was also reviewed, as it was used extensively in a previous study (Drake et al. 2012). Data packages for AMS designation were reviewed for nine *models* of BWMS: OceanSaver AS (OceanSaver MK I and MK II); Cathelco Ltd. (Cathelco); JFE (BallastAce I and II); Samsung (Purimar I and II); Auramarine (Crystal Ballast); Erma First (Erma First).

The AMS application data packages were reviewed to identify any filter subsystem test protocols or other means of qualifying the multiple filters identified by each manufacturer. In some cases, a manufacturer appeared to have developed his or her own filter, but listed an alternate supplier (e.g., Samsung), while other manufacturers depended entirely on external manufacturers to supply filtration systems. In one case, different filters were used on different models of a system, but multiple filters were not specified for either model (e.g., OceanSaver MK I vs. MK II). In all cases, specified filters were capable of automatic self-cleaning.

Of the AMS data packages reviewed, none identified how filters for a given BWMS were either specified or qualified. In one case, the manufacturer (Samsung) stated why a new type of filter was specified: performance enhancements (backwash pressure and improved rating for water resistance) were cited as justification of using a new filter type. In this case, the filter was manufactured internally instead of procured from an external supplier. While minimum and maximum flow rates, filter pore size, filter construction, filter cleaning method, pressure differential, and control system all affect how a filter may interact with downstream treatment equipment, in general, only the filter pore size and type of filter are specified in the AMS technical documentation. One manufacturer (Cathelco) provided data comparing an alternate filter to the base filter. This work was done at the Royal Netherlands Institute for Sea Research (NIOZ), using ambient water to quantify the removal and number of living organisms ≥50 μm and technical performance of the filters (backflush frequency and differential pressure). Some documentation packages referenced filter test reports, and one provided filter drawings (Samsung). However, filter test data were provided in only one of the packages reviewed (Cathelco). Of note, each of these manufacturers established a requirement for a filter in the overall process of treatment, indicating that subsequent, downstream treatment processes benefit from or require this filtration. No BWMS manufacturer cited a relationship between filter performance and overall treatment efficacy.

4.1 Filter Manufacturer Testing Summary

To further inform research on filter testing, filter manufacturers were contacted by the authors to request information on their product qualification testing. A series of questions was prepared to elicit information during a phone interview that covered test methods and protocols, aperture sizing, challenge conditions, productions tests, computational fluid dynamics (CFD) modeling, corrosion resistant coatings, cathodic protection, installation requirements, and other information offered by the vendors. Attempts were made to contact suppliers with US telephone numbers by telephone, and those without US offices were approached by email. Responses were received from (and conversations ensued) with three manufacturers: Amiad (parent of Arkal), Hydac, and Filtersafe®. Each identified superiorities of their filtration approach for ballast water applications, confirmed the existence of quality control programs to assure product consistency (including with regard to filter pore sizing), and indicated that both product development and challenge testing for ballast water applications have been done over many years. These manufacturers performed testing at many of the facilities in the ballast test community, including NIOZ, Norwegian Institute of Water Research (NIVA), Danish Hydrological Institute (DHI), Marine Eco Analytics (MEA), the Maritime Environmental Resource Center (MERC), and the Great Ships Initiative (GSI). Tests by each filter manufacturer were performed both independent

of and in conjunction with a BWMS. None of the filter vendors contacted claimed to perform in-house, full scale testing.

Each filter supplier indicated that tests were used to qualify pore size ratings of their filter material. While standard tests were mentioned (e.g., bubble tests, glass bead tests), specific protocols were not always cited or provided. However, any tests cited were included in the survey of standard methods presented in Section 5.

4.1.1 FilterSafe®

Filtersafe® indicated they have used portside tests at a variety of locations during their product development, which currently targets only ballast water applications. Testing was performed using various filter configurations to evaluate the removal of total suspended solids (TSS), the removal of organisms, high load simulation and recovery, back wash efficiency, and continuous operations. In particular, screen materials used in their products are stated to be tested to ensure a minimum removal of 40-µm glass beads of 97% according to a standard protocol, although the protocol was not identified. Micron ratings of filters were stated to be in accordance with ISO 4782 and Society of Automotive Engineers (SAE) ARP901 standards (a bubble point test method). Scaling of filter capacities maintains a constant ratio for filter flux, and testing has been performed at multiple scales. Screen technology has been optimized for organism removal in the ≥50 µm size class while maximizing filter throughput and minimizing back wash flow. Filtersafe® prefers testing with TSS ranges above 100 ppm, preferably in the 200-300 ppm range. The TSS is composed of organic material with size distributions reflective of sediment found in ballast tanks (although neither the particle size distribution nor the composition was provided). They note that the downstream conditions can affect filter performance, in particular the backpressure, and they are planning to offer an outlet valve to provide pressure control as an option. In-house testing of products is limited to hydrostatic leak testing and controller operations; all full-scale flow testing is performed at outside test facilities.

Filtersafe® offers a series of suggested tests for comparison of ballast filter technologies. While specific challenge loads are not identified, one test examines removal of sediment loads via a volumetric TSS test, and another increases flow above the rated value for 20-30 min in order to "blind" the filter (forcing the filter into continuous backflush due to high loading) and then assess recovery when flow returns to rated value. They note that in comparing filters across manufacturers, it is important to compare total screen area and conduct tests at operating pressures of 1-2 bar (in their opinion, 1-2 bar is representative of the shipboard operating environment).

4.1.2 Amiad Filters

Amiad manufactures two types of filters used in ballast water: screen and disc filters. The manufacturer indicated that screen filters are currently more popular in ballast water applications, so little time was spent discussing the disc filters. The screen filters use a four-layer sandwich design with a course screen on the inside and outside surfaces with two layers of fine filter mesh sandwiched between the coarse layers. The filters, rated by nominal pore size (rather than absolute), use surface filtration to create a barrier to capture particles. Amiad indicated they have completed in-house testing on the Sea of Galilee for the screen filters

marketed for ballast water, but test results were not provided. The majority of testing related to ballast water filters has been completed at test facilities, such as GSI and DHI, which used a 250 $m^3 h^{-1}$ system challenged with biological organisms and organic materials. The representative from Amiad indicated that air bubble tests are used to rate the filter screen material but did not provide specific information regarding the test procedure. Amiad procures the filter screen material from an outside source but has a quality control procedure to periodically spot-check the mesh received; the methodology of the assessments were not discussed by the Amiad representative. Performance testing using organisms has not been conducted on filter units with flows rated higher than 250 $m^3 h^{-1}$. The representative indicated the larger units have the same ratio of flow rate to effective surface area as the 250 $m^3 h^{-1}$ system, so filters scale linearly (e.g., a 250 $m^3 h^{-1}$ system will have the same flow rate to effective surface area ratio as a 1,000 $m^3 h^{-1}$ system, as the total filter area is greater in the larger system). Different corrosion resistant-materials are available for the screens, and the carbon steel housings are normally protected with zinc anodes and a two-part epoxy coating.

4.1.3 Hydac

Hydac manufactures a filter that uses several candle filter elements arranged in parallel for ballast water applications. The candle filter elements, which use a plain weave stainless mesh filter element and different options for the weave type (such as wedge wire), is self-cleaning and operates in surface filtration. The mesh for the candle filter element is purchased from a third-party supplier and shaped by Hydac into the candle filter elements. The representative indicated that they procure the mesh element based on a nominal rating but did not indicate how the nominal rating is determined. He specified that quality control checks are performed on the filter mesh received from the third-party manufacturers. The representative indicated that the Hydac system has been tested as a stand-alone filter at GSI, and it has been tested as part of an overall BWMS in several locations. The tests at GSI used organisms, TSS, and particulate organic carbon (POC), but the representative was critical of the tests because he thought testing was not uniform—several filters with different nominal ratings and flow ratings were compared, rather than comparing systems of the same nominal and flow rating. In these tests, the filters were scaled based on the flow velocity through the filter element, so that the flow velocity was the same in a small unit was it was for a large filter, an approach similar to other manufacturers that use flow rate per surface area (flux). Hydac, however, uses flow velocity as a metric to rate their filters.

The Hydac representative indicated that all filters used in ballast water have the same goal of removing particles and organisms to ease the treatment operation downstream. He also indicated that the smaller, conical-shaped candle filters are more robust and less subject to deformity than a single conical screen, such as ones other manufacturers use. Finally, he mentioned the difference between filters depends on how filters retain materials, how often they are cleaned, how efficient the cleaning is, and how long a filter lasts in practice.

5 SURVEY OF STANDARD METHODS FOR FILTER TESTING

A review of standards used for testing filters showed that methods have been established by ASTM International (ASTM), the International Standards Organization (ISO), and European Standards (EN). Standards are typically promulgated to ensure (1) That manufactured products meet the performance requirements in a given industrial application and (2) To provide all product manufacturers a suite of tests that validates the performance of their product. Thus, the tests identified in a standard test reflect a common performance requirement for a given application, and the test may or may not be useful for evaluating the same product in a different application. The standards identified in this survey generally address filtration to provide sterile, non-toxic process water in the pharmaceutical industry (filtered to ≤0.2 µm), filtration for laboratory and research uses (<0.2 µm to ~100 µm), filtration of water in industrial and agricultural uses (typically >100 µm), and screening of particles or separation of solid materials (typically >20 µm). Using filters to manage ballast water is both a new application and an emerging market, so it is unsurprising that standards relevant to this application still need to be developed. In BWMS, filters are often specified with a nominal pore size in the range from ≥10 µm and <50 µm. Filter efficiency is often unspecified, but filters in most applications are evaluated by log reduction or percent removal. **In this search, no standard was found that quantified removal by the *absolute number* of particles passing through the filter.** This point is important, as the IMO and US discharge standards are numeric standards. While some standards provide a challenge consisting of a single organism or solids loading, none specifies an assemblage of organisms representative of organisms typically found in harbors or a suite of variable-sized and malleable particles that could simulate organisms in aquatic communities.

5.1 Standards and Test Methods for Filters

Published standards were reviewed to determine if (1) There is a common method for evaluating the aperture sizes of ballast water filter and (2) If other test methods might apply to testing of ballast water filters (Table 2). Currently, no common, recognized test evaluates filters used specifically for the ballast water industry. None of the standards uses organisms and sediment for filter evaluations; regardless, some of the test components may be useful in developing a protocol for ballast water filters. Standards in Table 2 use organisms such as the bacterium *Serratia marcescens* or the protozoan *Cryptosporidium* sp. to measure the filter removal efficiency in pre- and post- filter samples, but these organisms are more applicable for testing systems designed for drinking water treatment (including systems where the filter is used as part of a reverse osmosis treatment). These tests likely do not apply to ballast water filters because these organism sizes are much smaller than the organisms regulated in ballast water (i.e., organisms ≥50 µm or ≥10 µm and <50 µm). Furthermore, some of the standards specify common methods to evaluate physical attributes of the filter element, such as the size of aperture openings. For instance, ISO 14315 and ISO 2591 indicate specific measurement procedures for determining the aperture size for woven metal wire screens and woven metal cloth. The measurements are normally captured using a flat section of the metal wire screen or metal cloth, and it is possible measured aperture size will change when the piece is curled into a cylinder, as is often the case for ballast water filters. Additional standards for the sizing of wire mesh apertures and validating products are provided in Appendix C.

5.1.1 Filter Performance Comparisons in Other Applications

Other industries have needed to compare filters of dissimilar filter technologies. The oil filter industry has developed a multi-pass protocol to specify filter ratings, and the industry defines the comparison metric as the beta ratio (ß). The beta ratio is different from the micron rating, as it was developed based on tests of the filter under controlled conditions and gives confidence in the rating of the filter performance.

In the residential heating and air conditioning industry, it is common for several different filter types to be used, such as high efficiency particulate absorption, bag filters, box filters, cartridge filters, electrostatic filters, etc. Four standard methods have been developed to evaluate particle removal efficiency in air filters: (1) Weight arrestance test, (2) Atmospheric dust spot efficiency test, (3) Dioctyl phthalate (DOP) penetration test, and (4) Particle size (EPA 2014). The tests use different challenge conditions, different particle sizes, and are specific to the type of filter being tested. To compare the results of all of the filter tests, a measurement scale was developed by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), the minimum efficiency reporting value (MERV rating). The MERV rating scales from 1 to 20 and has specific particle size removal efficiency or dust spot efficiency thresholds established via various test protocols. The MERV rating table is included as Appendix D. As an example, a filter with a MERV rating of 20 can remove ≥99.999% of all particles larger than 0.1 µm. A filter with a MERV rating of 16 can remove >95% of particles in the 0.3-1 µm size class, >95% of particles in the 1-3 µm size class, and >95% of particles in the 3-10 µm size class.

Table 2. Test methods used for evaluating filter performance in industries other than ballast water treatment.

Standard Organization	Standard Name	Year	Standard Number	Attributes of standard that are applicable to BW filters
Standard tests procedures used to compare different filters for a given application				
ASTM	Standard Test Method for Retention Characteristics of **0.40 to 0.45-µm Membrane** Filters Used in Routine Filtration Procedures for the Evaluation of Microbiological Water Quality	2011	ASTM D3863-87 (Reapproved 2011)	Measures retention efficiency of organisms larger than 0.45 µm (the bacterium *Serratia marcescens*) pre- and post-filter; not currently applicable to BW testing, as organisms in this size class are not currently regulated
ASTM	Standard Test Method for Silt Density Index (SDI) of Water	2014	ASTM D4189-01	Evaluates SDI via rate of plugging of a 0.45 µm membrane filter from challenge water under constant pressure; may be a useful parameter for comparison using a different test design for ballast water filters
EPA	Membrane Filtration Guidance Manual	2005	EPA 815-R-06-009	Challenge tests to determine removal efficiency of a specific target organism (*Cryptosporidium* sp.) for 1-µm membrane filters; may be useful in developing test procedures to evaluate BW filters using challenge conditions such as organisms and sediment load
EPA	ETV Generic Protocol for the Product Specific Challenge Testing of Bag and Cartridge Filters	2012	12/01/EPAD WCTR	Describes challenge tests of bag and cartridge filters for removal of *Cryptosporidium* sp.; may be useful in developing procedures to evaluate BW filters under challenge conditions of organism and sediment load
ISO	Hydraulic fluid power—Filters—Multi-pass method for evaluating filtration performance of a filter element	2008	ISO 16889:2008	Describes test to evaluate performance of oil filter elements using ISO test dust and particle counters (pre- and post-filter) to determine the beta ratio; a calibration suspension is specified to ensure the particle counters are accurate, traceable, and repeatable; this test provides a framework for establishing a comparison ratio

Standard Organization	Standard Name	Year	Standard Number	Attributes of standard that are applicable to BW filters
EN	Water conditioning equipment inside buildings – Mechanical filters **–** Part 2: **Particle rating 1 µm to <80 µm –** Requirements for performance, safety and testing	2007	EN 13443-2:2005+A1:2007	Methods for assessing the construction and performance of mechanical filters used for drinking water in buildings with a minimum nominal inlet pressure of 6 bar; includes bubble point and challenge tests using ISO test dust under alternating conditions of high and low loads. Procedures and test setups are defined for: reference filtration rating from cumulative and differential filtration efficiencies, retention capacity, differential pressure, cartridge collapse pressure, cartridge cyclic pressure resistance, particle shedding, housing pressure and cyclic pressure tests; this standard applies to a similar size range as used in BW filtration, and some procedures may be applicable to BW filter tests
Standard methods used to characterize filter test conditions				
ASTM	Standard Test Method for the Continuous Measurement of Turbidity Above 1 Turbidity Unit (TU)	2012	ASTM D7725-12	Describes methods for measuring turbidity in drinking water, process water, and high purity industrial water; measurement techniques may be applicable in BW filters tests
ASTM	Standard Guide for The Use of Various Turbidimeter Technologies for Measurement of Turbidity in Water	2011	ASTM D7726-11	Best practice guide for selecting turbidity meters; may be useful in selecting test equipment for evaluating turbidity in BW filter tests
ASTM	Standard Practice for Comparing Particle Size in the Use of Alternative types of Particle Counters	2013	ASTM F660-83	Procedure for comparing sizes of nonspherical particles using different particle counter methodologies; useful as a reference where particle counters are used in BW testing
Test standards and requirements for sieves and filter materials				
ISO	Test sieves and test sieving—Vocabulary	1990	ISO 2395:1990	Defines common terminology in evaluation of test sieves; no test procedures are defined in this standard

Standard Organization	Standard Name	Year	Standard Number	Attributes of standard that are applicable to BW filters
ISO	Industrial wire screens—Technical requirements and testing	1997	ISO 14315	Describes procedure to measure aperture sizes in wire screen meshes; may apply to BW filters that use industrial wire screens
ISO	Test sieves—Technical requirements and testing—Part 1: Test sieves of metal wire cloth	2000	ISO 3310:2000(E)	Describes technical requirements and test methods for metal wire sieves with aperture sizes from 20 µm to 125 mm, including visual inspection, microscopy, and requisite documentation; may apply to BW filters that use metal wire cloth
ISO	Test sieving—Part 1: Methods using test sieves of woven wire cloth and perforated metal plate	1988	ISO 2591-1:1988(E)	Describes use of a sieve or perforated metal plate; not applicable to BW filter tests
ISO	Test sieves—Metal wire cloth, perforated metal plate and electroformed sheet—Nominal sizes of openings	1990	ISO 565	Specifies nominal size measurement for metal wire cloth, perforated metal plate, and electroformed sheet used in test sieving per ISO 2591-1:1988(E); not applicable to BW testing

ASTM = ASTM International, BW = ballast water, EPA = Environmental Protection Agency, EN = European Standard, ISO = International Organization for Standardization, SDU = Silt Density Index, and TU = turbidity unit.

Given the variety in existing standards, and the lack of specific applicability to ballast water filters, it seems appropriate to collect tests with appropriate features in a protocol specific to ballast water filter testing. A new test(s) could assess organism removal in the ≥10 and <50 µm and ≥50 µm size ranges, TSS loading, flows between 200 and 1,000 $m^3 h^{-1}$ (typically found in ballast water applications), and inlet pressures. Such protocols could be developed from existing filter evaluation information and test methods combined with some new methods (as described in other sections of this paper) to ensure filters are evaluated consistently and with the highest degree of accuracy. Developing a comparison metric, such as the beta ratio or MERV rating would be exceptionally useful for stakeholders that might want to interchange different ballast water filters in BWMS, because it would accurately compare filters without having to rely only on the nominal rating as currently supplied by vendors of filters.

6 RECENT EVALUATIONS OF COMMERCIAL FILTERS FOR BWM APPLICATIONS

Recently, studies have been performed to assess the performance of a filter (or filters) independent of an associated BWMS. The methods employed in these evaluations differ from standard test protocols discussed above because they include assemblages of live organisms as well as organic and mineral solids, sourced from ambient waters, and they were specific to BWMS filters. In some cases, organisms or water quality parameters were augmented to meet minimum challenge water conditions. Notably, different assemblages of organisms pose varying degrees of difficulty for filters, so comparing tests conducted in different locations is relevant when assessing a filter's efficacy. It is not surprising, then, that one of the papers concludes that testing at multiple locations is necessary to assess filter performance.

6.1 Filter Study – Great Ships Initiative (GSI)

At GSI, a land-based, freshwater test facility (TF) in Superior, WI, a test of commercially available filters was conducted to evaluate their performance (Cangelosi et al. 2014). Eight commercially-available-off-the-shelf (COTS) filters were tested in groups of two over a period of five weeks (September - October 2013). Here, ambient organisms as well as TSS were used to challenge filters at realistic flow rates. Because GSI could not ensure conditions were exactly the same over all tests, parameters were monitored and analyzed to determine any significant differences among tests. The results showed the biological communities had similar compositions over all of the tests.

The eight filters tested had nominal pore size (as specified by the vendor) ranging from 10 to 40 µm: 10 µm (1), 20 µm (1), 25 µm (1), 30 µm (1), and 40 µm (4). The filters had different configurations: polyolefin (1), candle (1), screen (3), and multi-screen (3). Likewise, their target flow rates, as specified by the manufacturer, varied: 150 $m^3 h^{-1}$ (1), 200 $m^3 h^{-1}$ (1), 250 $m^3 h^{-1}$ (3), 300 $m^3 h^{-1}$ (1), and 340 $m^3 h^{-1}$ (2). Because four filters had nominal pore sizes of 40 µm, an opportunity emerged to compare multiple filter types having the same nominal pore sizes:

configurations ranged from candle, screen, and multiscreen, and the target flow rates ranged from 200 - 340 $m^3 h^{-1}$.

Each filter was subjected to four test cycles lasting 3 – 4 h, with one cycle per day. The total volume of water filtered was set at three-fold the manufacturer's flow rate per hour, e.g., for a design flow rate of 200 $m^3 h^{-1}$, a total of 600 m^3 was filtered, with three "unit volumes" of 200 m^3. In each test cycle, the first two unit volumes consisted of ambient water from Duluth-Superior Harbor (adjacent to the TF); the third unit volume consisted of ambient water augmented with TSS to meet a minimum target concentration of 24 mg L^{-1} (with is stipulated in the ETV Protocol). The following operational parameters were quantified: volumetric flow supplied by the TF to the filter, the flow throughput of the filter, the backflush flow ratio, and pre-, post-, and differential pressure across filters.

The analyses for organisms and water chemistry parameters were conducted following GSI standard operating procedures (SOPs) techniques that generally follow the ETV Protocol. Two deviations should be noted. First the analysis of organisms in the ≥10 µm and <50 µm size class (nominally protists) differs in that only one fluorochrome was used, rather than the two prescribed in the ETV Protocol; this change has been validated by GSI (Reavie et al. 2010). Second, because organisms ≥50 µm at GSI are dominated by rotifers approximately 50 µm in size, this size category was divided into "microzooplankton" (soft-bodied zooplankters near the 50 µm threshold) and "macrozooplankton" (larger, hard-bodied zooplankton). In BE tests, results were quantified in percent reduction from intake and absolute numbers.

With respect to water quality conditions, an important parameter to challenge filters is TSS. In the test cycles augmented with TSS, the percent removal of TSS varied over all filters from 11 – 63%. When the four 40 µm filters are considered, the variation was smaller. It ranged from 11 – 21%.

The percent reduction in organisms ≥10 µm and <50 µm ranged from 22 - 89%, and for organisms ≥50 µm, it ranged from 31 - 99.9%. There was a significant, negative correlation between nominal pore size and percent removal of microzooplankton and protists, that is, removal generally increased as the pore size of filter decreased. In contrast to that generality, there were instances where a smaller filter (20 or 25 µm) performed worse than a larger filter (30 µm). Interestingly, the removal of organisms varied greatly among the 40-µm filters: the percent removal of microzooplankton ranged from 37 - 96%, with input conditions differing little, from 321 x 10^5 vs. 323 x 10^5 organisms m^{-3}, respectively, a difference of <2%

The biological performance did not track (positively or negatively) with the operational performance parameters measured; the volume lost to backflushing did not seem to correlate with increased organism removal, although the report noted that unmeasured parameters (e.g., energy consumption) might have increased. Regardless, one lesson from this study is that filters with different pore (aperture) sizes obtained different results, which supports requiring empirical testing (rather than a paper study) for evaluating equivalence between filters.

In this study, manufacturers did not submit specific information about the filter elements. In evaluating filters, it would be helpful to require manufacturers to supply geometric information

about the filter aperture sizes and how this was determined. For example, the ISO 14315 standard for industrial wire screen may be used to benchmark the filter parameters.

6.2 Filter Study – Department of Fisheries and Oceans Canada

In a study of ballast water filtration efficacy conducted by the Department of Fisheries and Oceans Canada, biological samples were collected during the summer of 2012 on the bulk carrier M/V Richelieu at three ballasting locations in the Great Lakes (Briski et al. 2014). Ballast water samples were collected at both the filter inlet and outlet, with samples collected at the beginning, middle, and end of the ballasting operation. Ballast flow capacity of 600 $m^3 h^{-1}$ was available on independent port and starboard ballast systems, and each side had a dedicated filter. Testing was performed only on the starboard side due to access issues, typically at flows of 300 $m^3 h^{-1}$. The shipboard filter incorporated a 40-µm stainless steel mesh within cylindrical candle elements in an automatic backflushing system (Hydac International AutoFilt RFU-5).

Results showed that the three locations provided notable biodiversity even though all were within the Great Lakes, and large variations were observed in percentage removal of zooplankton and phytoplankton as well backflush operations when one filter was tested at different sites. Notably, the filter provided significant reduction in the phytoplankton concentrations as well as the adult zooplankton concentrations. The percentage of zooplankton removed from ballast water at three locations (Quebec City, Sarnia, and Thunder Bay) was 17, 73, and 51%, respectively, and phytoplankton removal was 61, 62, and 26%, respectively. At the Thunder Bay location, higher densities of a zooplankter with a large, gelatinous mantle affected filter loading, resulting in higher rates of backflushing, reduced ballast flow, and nearly 30% longer ballast times. The effects of TSS or other water chemistry parameters were not assessed. The authors concluded that testing filters at a variety of locations is necessary to assess filter performance in multiple ecosystems and "ensure global suitability".

6.3 Filter Study – Maritime Environmental Resource Center (MERC)

Independent performance testing and technology evaluations of ballast treatment technologies are conducted at MERC, which was contracted to perform evaluations of the Filtrex ACB filter by the manufacturer. Here, land-based testing on three configurations of the filter was performed, with mesh size ratings of 6, 20, and 30 µm (MERC 2014). The tests were performed in the upper Chesapeake Bay during the fall of 2013. Each filter size was tested once with natural (ambient) water and a second time with ambient water augmented to increase levels of TSS and POC to concentrations specified in the ETV Protocol. For each test, the manufacturer selected set points for feed flow and backpressure to the filter based on commissioning trials. An extra test of the 30-µm filter was performed at a different flow rate with ambient water, but augmented testing was cancelled due to adverse weather. A total of 7 independent tests were conducted.

To assess filter performance, concentrations of live organism in both uptake and filtered water were measured for the ≥10 µm and <50 µm and the ≥50 µm size classes. Ambient uptake

concentration in both classes varied by an order of magnitude over the tests; the overall ranges for the two size classes are provided in Table 3. In addition, water quality parameters were recorded at sample points at pre- and post-filter locations. The salinity for all tests was brackish (ranging of 9 to 12 practical salinity units [psu]). The temperature of the source water ranged between 6 and 15 °C, with dissolved oxygen levels between 7.3 and 14.2 mg L^{-1}. The ranges of TSS and POC for natural and augmented uptake water are provided in Table 4.

Table 3. Natural uptake organism densities in filter testing at MERC.

Size class	Range of living organisms
≥50 µm	32,000 to 233,000 (organisms m^{-3})
≥10 to <50 µm	1,100 to 15,000 (organisms mL^{-1})

Table 4. Natural and augmented water chemistry parameters in filter testing at MERC.

Water type	TSS (mg L^{-1})	POC (mg L^{-1})
Natural	1.9 - 5.8	0.67 - 2.13
Augmented	30.4 - 55.2	3.5 - 4.6

POC = particulate organic carbon, and TSS = total suspended solids

The results reported by MERC were direct counts of live organisms in the pre- and post-filter water samples, observations on the plankton taxa in the samples, and concentrations of chlorophyll *a*. Water quality parameters identified above were also reported for each test. Smaller mesh sizes removed greater quantities (and percentages) of both organism size classes. The report noted that the manufacturer performed independent hydraulic tests and monitored instantaneous flow rate, daily accumulated flow, filter differential pressure, and the number of backwashes during the day; these data were not reported.

6.4 Filter Study Protocols – NIOZ

The Royal Netherlands Institute for Sea Research (NIOZ) offers a performance test for BWMS filters on its test vessels: Navicula and Pelagia (NIOZ 2014). The Navicula is where pilot studies of BWMS are often conducted, and the Pelagia is used when flow rates for testing exceed 250 m^3 h^{-1}. The tests use seawater or 600 m^3 batches of fresh water. Technical details about the individual test sites are included in the test protocol (not listed here) and describe the pump capacities, tanks, augmentation equipment, power, data logging, and other pertinent technical information for both test vessels.

The test procedures vary and depend on the customer requirements, type of filter, filter aperture size, and time requirements (Peperzak 2014a). In total, NIOZ offers six standard operational tests that range in difficulty between a test using natural water to a "Shanghai" test (described below) with high TSS concentrations added to the test water. Five challenge water options are

also available to test and evaluate filters. The six operational tests and five challenge water options are summarized in Table 5. Additionally, NIOZ offers BWMS vendors the option to experiment using the NIOZ facility prior to setting up a specific test. The experimentation period allows the vendor to change filter screens or examine flow rates before operating a specific test protocol for TA testing.

Table 5. Operational test conditions and challenge water loading options for filter testing at the Royal Netherlands Institute for Sea Research (NIOZ).

Parameter	Operational Conditions
Operation and maintenance test	≥6 hours using natural water
Flow rate	Varying flow rates, 100-250 $m^3 h^{-1}$
Filter performance	Test by increasing TSS loads from 10 to >200 mg L^{-1} until filter starts continuous backflush
Filter recovery time	Evaluate clogging with extreme TSS load
Operational test with TSS loading	Changing TSS loads (10 to >100 mg L^{-1}) to maximum filter capacity (continuous backflushing)
Challenge water: Ambient harbor water	≤200,000 m^{-3} for >50 µm size class ≤8,000 org. L^{-1} of >10 to ≤50 µm size class 10 to 50 mg L^{-1} of TSS 20 to 35 psu salinity
Challenge water: Augmented harbor water	Harbor water augmented with natural marine or artificial TSS up to 200 mg L^{-1}
Challenge water: Fresh water	≤250,000 m^{-3} for >50 µm size class ≤2,000 org L^{-1} of >10 to ≤50 µm size class 10 mg L^{-1} of TSS with augmentation available up to 200 mg L^{-1} <1 psu salinity
Challenge water: Shanghai test	TSS up to 1,000 mg L^{-1}

TSS = Total suspended solids, and psu = practical salinity units.

Researchers at NIOZ measure several parameters during filter tests; these are categorized as BWMS-specific variables, performance measurements, and laboratory analysis (Table 6). Some of the measurements are filter-specific, and some overlap with measurements conducted during IMO or ETV BE testing.

Table 6. Measurements collected by NIOZ during ballast water filter performance testing.

Type of Measurement or Analysis	Specific Measurement or Analysis Technique Used
BWMS-specific measurements	Flow rates: intake, discharge and backflush
	In-line turbidity
	Differential pressure before and after filter
	Count of cleaning cycles
Performance measurements	Backflush frequency
	Flow rates before and after the filter
	Filter throughput
	Duration of backflush cycle
	Removal efficiency of organisms >50 µm organisms (only during O&M test)
	Removal efficiency of organisms >10 µm to ≤50 µm and >25 µm to ≤50 µm (only during O&M test)
	Removal efficiency of natural TSS
	Other measurements on request
Laboratory analyses	Abundance and diversity for organisms >50 µm
	Abundance and size distribution for organisms >10 µm to ≤50 µm using flow cytometry and microscopy
	TSS concentration using GF/C or GF/F filters
	Particulate organism carbon (POC) and mineral matter (MM) content
	Particle size distribution using laser diffraction or flow cytometry
	Particle imaging using FlowCAM, flow cytometry, or microscopy
	Other biotic or abiotic analyses on request

GF/C = Glass microfiber filter (coarse), GF/F = glass microfiber filter (fine), and O&M = operations and maintenance.

All tests of filters follow the NIOZ Quality Management Plan, and analyses are conducted per NIOZ standard operating procedures (SOP). The several calculations described in the test protocol include filter efficiency, number of backflushes, filter throughput, in-line turbidity, and TSS (summarized in Table 7). The calculations appear straightforward, but the calculations for backflush duration and mean backflush time may need further clarification.

Table 7. Summary of calculations used in NIOZ filter testing.

Calculation	Equation
Filter efficiency	% Efficiency = (M_{intake} - $M_{discharge}$)*100%/ M_{intake} *M* can be any variable, such as organism concentration or TSS
Number of backflushes	Count of backflushes that occurred over 6 hour O&M test
Backflush duration	Three 5-minute time windows are examined on the in the intake flow rate versus time plot to determine length of backflush
Mean backflush time	Mean backflush time is calculated from all backflush cycle durations in the total 15-minute time period examine in the previous row
Filter throughput	% Throughput = (Flow rate post-filter)/(Flow rate pre-filter)*100% Post filter flow rate is the average flow rate over an extended period, and the pre-filter flow rate is the flow rate when setup to run in filter bypass mode
TSS based on in-line turbidity	TSS = (FNU-0.5)/0.45 The relationship between turbidity (FNU) and TSS is site-specific and determined from NIOZ harbor water and mud that may be added

FNU = formazin nephelometric unit, *M* = any variable such as organism concentration or TSS, NIOZ = Royal Netherlands Institute for Sea Research, O&M = operations and maintenance, and TSS = total suspended solids.

6.4.1 NIOZ "Shanghai Test"

The "Shanghai Test" was developed to test ballast water filters with suspended solids or mud concentrations that are similar to the conditions in Shanghai harbor, China (Peperzak 2014b), which is famously turbid. NIOZ researchers found a proxy with a similar particle size distribution and carbon content to mud in Shanghai harbor. Next, they developed methods for suspending the proxy mud in test water and measuring the concentration in-line with a turbidity sensor as TSS. The mud concentration is pumped from a tank and injected into the main ballast flow line, where it mixes with intake water. The concentration of TSS is varied by changing the mud flow rate, and the test can be conducted at concentrations up to 2000 mg L^{-1}. Concentrations of TSS are increased in steps of 100 mg L^{-1} until the filter clogs or the BWMS is in continuous backflush.

7 RECOMMENDATIONS FOR APPROVING ALTERNATE FILTERS IN BWMS

The USCG may be approached by a vendor requesting TA for a BWMS that will use multiple filters, but the TA tests will have been conducted using only one filter. In this instance, a range of data collection or testing could be requested of the vendor (Table 8). The most straightforward (and lowest-cost) option is to conduct a paper study to compare the characteristics of the original filter to an additional, alternate filter(s) to assess equivalency. In increasingly complex scenarios, additional testing could be required, ranging from testing the filter component according to international standards to a full complement of land-based and shipboard testing for every additional filter.

Table 8. Options for testing ballast water management systems (BWMS) with multiple filters after the initial BWMS (with the original filter) has been type approved.

Options for Each Alternate Filter	Time to Complete	Expense (Low, Medium, High, Very High)	Caveats (Drawbacks of the Option that may Influence the Comparability of Filters)
Compare original filter used in TA to alternate (a paper study)	Days	Low	Even if filters have the same pore size, their effectiveness may be different
Use computational fluid dynamics modeling to model flow through filter	Weeks	Medium	Models are inherently theoretical approximations and are prone to error. Typically, models address flow characteristics but not organism removal
Test filter following standardized protocols for filter testing (e.g., ISO) at a laboratory or land-based TF with inorganic tracers (e.g., sediment or microbeads)	Days – Weeks	Medium	While sediment or microbeads will challenge filters' efficacy, they do not completely represent all of the challenge conditions (e.g., motile organisms of different shapes interspersed with other suspended solids)
Test filter with STOs (e.g., *Artemia* sp.) and microbeads at a land-based TF	Days – Weeks	Medium	While one STO will challenge filters' efficacy, STOs do not represent all of the challenge conditions (e.g., taxonomic diversity)

Options for Each Alternate Filter	Time to Complete	Expense (Low, Medium, High, Very High)	Caveats (Drawbacks of the Option that may Influence the Comparability of Filters)
Test the original and alternate filter at a land-based facility using the challenge water parameters stipulated in the ETV Protocol*; testing could occur with 5 tests at a given salinity or fewer tests	Weeks-Months	High	Testing at only a land-based facility and not onboard a ship will not capture real-world operating conditions
Conduct a design study and additional land-based, O&M testing, and component testing	Weeks-Months	High-Very high	The testing is not quite as rigorous as full TA testing
Test the entire BWMS with alternate filter using the challenge water parameters stipulated in the ETV Protocol at a land-based facility (5 tests per salinity) and aboard a ship following the stipulations in the US regulations for TA	Months	Very High	None

*This test would be conducted following a new protocol developed specifically for BWMS filters. ETV = Environmental Technology Verification Program Protocol, ISO = International Organization for Standardization, O&M = operations and maintenance, STO = standard test organism, TA = type approval, and TF = test facility.

7.1 Approving Alternate Filters– Three Approaches

In this section, two recommended approaches are considered. A third—less desirable—approach is also discussed. If the first two approaches, which use full-scale testing of a filter installed in the BWMS, cannot be employed, the third, which involves testing filters independent of the BWMS, may be necessary. Note that the third approach would take a relatively long time to implement (months), whereas the first two approaches can be implemented immediately. Regardless, the third option should be pursued, as it could (eventually) be shown to effectively compare filters and thus reduce the testing burden on BWMS vendors and test facilities (TFs).

7.1.1 Recommended Approach: Full-Scale Testing

Clearly, the most complete, rigorous, and highly recommended (based on the authors' technical expertise) approach to assess the efficacy of different filter components—and the approach that

would yield the most confidence in the results—is through full verification testing of the BWMS with each alternate filter (the last row of Table 8). This testing would include land-based, shipboard, component, and active substances (if appropriate) testing. As noted above (Section 1.1), US regulations can be interpreted to require TA for each combination of filter and associated BWMS, so the default approach is that the BWMS would undergo the full suite of land-based and shipboard testing for each filter. Given some vendors may stipulate several filters (and other components, such as alternate UV reactors), this approach would likely be prohibitive in the great cost and time required.

7.1.2 Recommended Approach: Design Study and Additional Land-Based, Operations and Maintenance (O&M), and Component Testing

In the absence of full TA testing for each alternate filter, it is recommended, as an interim solution, that each alternate filter be subject to a reduced version of TA testing. First, a design study should be conducted by comparing filter and BWMS specifications to document that the alternate filter meets or exceeds requirements for replacing the original filter, and that performance is consistent with the requirements of the downstream treatment. For example, if an original filter has a flow range of 60 to 500 $m^3\ h^{-1}$, and a flow capacity of 30 to 300 $m^3\ h^{-1}$ is required in the BWMS, an alternate filter with a flow range of 30-355 $m^3\ h^{-1}$ would be shown (though the design study) to be better matched to the treatment system flow than the original filter. In this example, the alternate filter's minimum flow range is the same as the secondary treatment minimum, while the maximum flow exceeds that of the secondary treatment.

Comparisons would proceed according to the draft criteria provided in Table 9, and the TF should add any other criteria deemed useful. For each parameter, the alternate filter would need to demonstrate equivalence or shown to be better than the original filter. For instance, the alternate filter should work as seamlessly or better with the downstream components and any changes to the overall maintenance requirements of the system will be documented. Additionally, the BE of the alternate filter tested as part of the full BWMS must be equivalent or better than the original filter when tested at a land-based facility (see next paragraph). The filter manufacturer's quality certification (and any other assurances of manufacturing consistency) should be also provided. Finally, any test data should also be included, for example, tests conducted by the filter manufacturer to assess filter performance (independent of a BWMS). Importantly, manufacturer-generated data is prohibited from being used for US TA (USCG 2012).

Table 9. Draft characteristics to assess equivalence among filters in a design study.

Design and Interface Characteristics	
Filter Design	
Criterion	**Specification**
Filter rating	Rating; this can be nominal, absolute, or another method (see Appendix A). The test method used to determine the filter rating should be specified and data provided
Effective filtration area (cm^2 or m^2)	Wetted surface area that is available for filtration; this area calculation should subtract any solid barrier that obstructs fluid flow or particle separation
Filtration velocity	Rated flow rate vs. effective surface area for a clean filter. As an example, in a metric system this will be defined as meters per hour ($m^3\ h^{-1}\ m^{-2} = m\ h^{-1}$).
Linear filter scaling	Examines filtration velocity across all rated capacities; when not constant, the reference to design guidance and performance test data should be cited
Porosity defined from pore size, shape, spacing	Porosity; cite standard, if applicable
Filter material	Material, e.g., woven stainless steel, nylon disks
Filtration method	Method, e.g., surface filtration, depth filtration
Filter construction	Construction, e.g., screen, candle, grooved disk, cartridge, membrane
Cleaning method	Method, e.g., suction screen back wash, replacement of filter cartridge
Filter Inlet and Outlet Pipe Diameter (mm)	Diameter of the inlet and outlet of filter being tested. Indicate type of connection to downstream equipment (e.g., flange connections)
Operational Interfaces	
Criterion	**Specification**
Control status outputs	Status signals available for monitoring by the BWMS
Control command inputs	Command signals available for control by the BWMS
Alarm signal outputs	Alarm signals provided for external monitoring by the BWMS
Alarm or fault indicators	Audible or visible alarms provided by the filter
Air requirements	Pneumatic supply volume and pressure requirements
Fresh water requirements	Volume and flow requirements for fresh water supply
Electrical supply requirements	Voltage, current and number of phases required to power the filter
Mechanical Design and Construction	
Criterion	**Specification**
Housing material(s)	Materials used for the filter housing
Exterior coatings	Any coatings used for exterior protection
Wetted surface coatings	Any coatings used for interior (wetted surface) protection
Corrosion protection features	Corrosion protection features, such as galvanic anodes
Orientation requirements	Specific mounting orientation for the filter (if any)

Design and Interface Characteristics	
Maintenance Requirements	
Criterion	**Specification**
Filter surface maintenance	Inspection or expected maintenance intervals
Sensor calibration	Calibration intervals for all pressure and other sensor types
Valves	Inspection or expected maintenance intervals
Motors and drives	Inspection or expected maintenance intervals
Actuators	Inspection or expected maintenance intervals
Cleaning components	Inspection or expected maintenance intervals
Clear space maintenance dimensions	Required clear areas around each component that may require removal for maintenance after installation

Having established equivalence through the design study, additional empirical tests (with the filter installed in the BWMS) would be required. As a practical compromise, a full suite of five tests would not be conducted. Indeed, Det Norske Veritas Germanischer Lloyd (DNV-GL) has proposed that an alternate filter undergo reduced land-based testing (and no shipboard testing). In the DNV proposal, the filter is to be installed in the BWMS with testing to proceed under "full scope challenge water in accordance with the ETV protocol"—for three tests (with at least two salinities) for which the BWMS has already received TA (DNV-GL 2015). For reference, consistent with USCG regulations, TA testing consists of:

- Five consecutive, valid, successful replicate BE land-based tests meeting discharge standards for living organisms and active substances at each salinity
- Five consecutive, valid shipboard BE test cycles over ≥6 months that include and associated whole effluent toxicity (WET) tests that meet effluent discharge standards
- Use of the BWMS for *all* ballast discharge operations that occur in US waters during the test period
- Component testing under conditions of vibration, incline, temperature, humidity and power

To obtain TA for an alternate filter to be used in the BWMS (i.e., alternate filter with the secondary treatment) under this recommended approach, testing (with the alternate filter installed in the BWMS) consists of:

1. Three sequential, replicate BE land-based tests conducted using only ambient species with concentrations to meet ETV challenge densities at each salinity for which the BWMS will receive TA; running three, rather than five tests is a compromise that seems achievable while also yielding a reasonably large data set
   a. The results of the BE tests from the tests using the alternate filter should be compared to the results of BE tests using the original filter (i.e., statistical analyses comparing the number of living organisms in each of the two largest size classes stipulated in the discharge standard)
2. No shipboard testing; because operation over 6 months that includes 5 shipboard BE tests will have been conducted with the original filter, the robustness of the overall BWMS

will have been tested, and additional O&M testing will further evaluate the alternate filter's performance (as per the next item)

3. O&M testing with ambient water with the BWMS equipped with the alternate filter and consisting of 50 hours operation at 80-100% of the treatment rated capacity (TRC) and 10 hours of operation at 0-20% TRC; and these numbers are recommended to ensure the alternate filter is capable of processing water at both high and low flow rates
    a. For reference, the ETV Protocol stipulates O&M testing of a minimum of 10,000 m^3 of water amongst the BE test cycles, amounting to approximately 50 h of operation at a rate of 200 $m^3\ h^{-1}$, although the flow rate is not specified
4. Component testing of the alternate filter will be conducted (if it includes electrical components); component testing of the entire BWMS will have been conducted with the original filter

7.1.3 Third Approach: Testing of Alternate Filters Independent of the Ballast Water Management System

Alternate filters could be assessed individually using modeling or empirical testing by comparing their performance to the original filter (while not installed in a BWMS). Such an assessment for individual filters is considered here. First, a design study would be completed (as discussed in Section 7.1.2). Using CFD modeling (without additional empirical testing) is one option to assess a filter's performance. Indeed, fluid dynamics models are useful to predict the distribution of flows and pressures in a well-constrained system. Models can be used in some cases to examine filtration, for example, ensuring a uniform flow distribution across or through filter media or to visualize flow within a chamber. Notably, establishing a model requires fixing boundary conditions and fluid properties. Due to the variable nature of both ballast water input conditions (a function of organism concentrations, sediment loading, etc.), defining a comprehensive suite of input conditions needed to predict filter performance over the expected operating range seems unrealistic. Additionally, each alternate filter would require its own model to be developed, and, of course, validated. Thus, while CFD modeling may be a useful tool in designing BWMS and choosing alternate filters, using it to assess the suitability of alternate filters—in the absence of empirical testing—is not recommended.

From the tests conducted by GSI (Cangelosi et al. 2014), it is clear that different filters—even with the same nominal pore size—show different particle removal efficacy under controlled conditions. Likewise, the tests conducted by Briski et al (2014) show that the same filter operates differently in various locations within the freshwater Great Lakes. While this study did not examine water chemistry parameters, the local assemblage of organisms was documented, and differences in biological communities at each location were identified as the reason for differences in filter performance at each location. This conclusion reinforces that filters need to be tested empirically in some fashion.

In this scenario using empirical testing, an entire BWMS would undergo TA testing, and then the original filter used in TA testing would be independently evaluated. The BE and the operational performance of the original filter would be quantified (outside the BWMS), and alternate filters would be tested in the same manner to establish equivalence with the filter used to gain TA. After equivalence was established via challenge testing, the original TA certificate would be modified to incorporate the equivalent filter(s).

This (filter) component testing would be conducted at a land-based facility. Shipboard testing of alternate filters would not be necessary: the environmental parameters can be strictly controlled in a land-based setting, and shipboard testing would have been conducted to determine the seaworthiness of the complete BWMS. The details of the protocol would be finalized at an expert workshop (see Section 7.1.3.2 below). Likewise, the acceptable equivalence would be determined at the workshop, for example, if the results of the alternate filter should not be significantly different at $\alpha = 0.05$.

Because many BWMS have obtained non-US TA and specified multiple filters with different manufacturers and modes of operation, these tests were reviewed for potential guidance on filter testing (Section 4). Examining a subset of the USCG AMS applications revealed no application included test data for each of the specified filters. Where test data was available, it identified data sets with only one filter, although different filters may have been used in land-based or shipboard testing. Additionally, no data packages addressed the criteria for filter performance required for operation as a subsystem within the BWMS; generally, they identified only the manufacturer and model of the specified filters. A few provided drawings for all sizes of filters specified. Therefore, the AMS applications did not provide a clear path forward for assessing alternate filters.

7.1.3.1 *Testing Alternate Filters – ETV Approach*

At a top level, the "philosophy" of the empirical testing is relevant. It is recommended that the testing conditions are consistent with the ETV Protocol's approach, i.e., "to verify a treatment system's performance using a set of challenging, but not rare, water quality conditions representative of the natural environment" (EPA 2010). Thus, the challenge water conditions used in filter testing should be those used in the ETV Protocol. As the ETV Protocol is updated, those changes should be incorporated into the filter protocol. For example, a study is underway to compare the challenge water conditions stipulated in the ETV Protocol to biological, chemical, and geological characteristics of harbor waters around the world. The outcome of the study should inform future updates to the ETV Protocol.

Congruent with the ETV philosophy, a protocol for conducting filter testing should be developed following the ETV model, that is, by convening expert working groups to best inform the protocol as experts provide theoretical input and describe practical experience. The workshop is discussed in the next section.

7.1.3.2 *Testing Alternate Filters –Workshop to Develop Protocol for Standardized Testing*

It is recommended that a workshop of experts is convened to develop a protocol for standardized ballast water filter testing. Here, a detailed protocol should be constructed, incorporating elements of existing test protocols and criteria (as above). This workshop should include expertise from ILs, TFs, and filter vendors. The following recommendations for testing (to be refined in the workshop) reflect a practical compromise to conducting a full suite of TA tests for every filter used with a given BWMS:

- Definitions for common filtration terminology will be discussed and agreed upon as they are applied to BWMS filters

  - The definitions in Table 1 will be discussed, and a consistent technique and equations will be used to define and compare flow rate, flux, filter rating, filter effective surface area, etc. The EPA membrane filtration guidance should be used as a model
- Consistent with US regulations, testing will be recommended at all salinities (with different biological communities) in which the BWMS is TAed for use
- The number of replicate tests per filter will be 3-5, using either the ETV Protocol's recommendation (3) or the US regulations (5) would likely be used, although existing data on the variability of filters' efficacy will be reviewed to inform the necessary number of trials, and mathematical modeling would be conducted (Section 7.1.3.3)
- Each test should process a volume equal to at least twice the rated capacity per hour when using ambient water, and at least equal to the rated capacity per hour for challenge water (from the ETV Protocol) (Cangelosi et al 2014)
- Data on the removal efficiency of organisms will be collected, comparing organism counts at inlet and outlet of the filter from time-integrated samples over the duration of each replicate test; data will be expressed as both logarithmic reductions (since filter manufacturers report efficacy in this manner), as well as numerical reductions (since the US regulations stipulate a numeric discharge standard; note that filters alone will not be used in BWMS to meet the discharge standard); tests will be conducted with ambient assemblages of organisms, rather than standard test organisms (STOs) given the field-scale approach needed
- Data on removal efficiency of TSS will be collected
  - The use of an additional "Shanghai" test or other high sediment challenge test will be discussed at the workshop
    - Shipowners may want to have data from such a test so they know what the recovery time is when filters operate under extremely challenging conditions
  - The appropriate particle size distribution will be discussed at the workshop; for reference, the ETV Protocol states that ISO 12103-1, A3 Medium Test Dust and ISO 12103-1, A4 Coarse Test Dust are allowed, having "a majority of particles in the 10 to 50 µm size"
- Operational data (e.g., the number of backflushes during testing) will be collected during all tests, and additional O&M testing will be recommended, with the time or throughput to be determined
- Relevant attributes of existing protocols for standardized testing of filters in other applications (Table 2) should be reviewed and incorporated as appropriate
- The variables that would need to be controlled for (e.g., flux rates) will be discussed
- How filters will be characterized (in addition to the vendor's characterization) will be discussed

7.1.3.3 Testing Alternate Filters—Determining the Appropriate Number of Empirical Tests

The number of independent, empirical, BE tests that are conducted will determine the power of the statistical analyses to discern whether results are significantly different from the discharge standard. To determine the number of BE tests that should be conducted, two approaches should be taken. Mathematical modeling—as well as existing data—should be used to inform this critically important parameter.

Prior research experience has indicated that organisms are distributed in the discharge according to the Poisson distribution (e.g., Lemieux et al. 2008, Miller et al. 2011). For this report,

preliminary probabilistic analyses were conducted (Microsoft Excel; Redmond, Washington) to calculate the mathematical probability of obtaining successful test results when a different number of tests (2, 3, or 5) were conducted (see supporting information in Appendix E). Here, it was assumed that each trial met the discharge standard when λ (the mean and variance) was <10 (i.e., the number of living organisms in the two largest size classes was <10 m^{-3} or <10 mL^{-1}). Note, however, that for each value determined for a given test, for example, 7 mL^{-1}, the value has its own probability distribution, with a likelihood of sampling a number of organisms larger or smaller than the true value (here, 7 mL^{-1}). Considering that distribution around each value resulting from a given test, simulations were run. Here probabilities were computed for given values of the organism density to determine the likelihood of two or three trials to show if any of the tests resulted in a failure (i.e., the discharge standard was exceeded) vs. five trials. The results showed that the closer the number of living organisms were to exceeding the discharge standard (slightly below or slightly above 10 m^{-3} or 10 mL^{-1}), the less reliable two or three tests were in uncovering the failure (Table 10). In addition, with more trials, the chances increased of at least one of the tests failing, even if the standard was technically being met (i.e., the true value was <10 m^{-3} or 10 mL^{-1}). The level of acceptable uncertainty stemming from the number of empirical tests will need to be determined, such exercises can be used to make this decision.

Table 10. Percent chance of passing test based on the number of trials, based on the probability distribution for the mean number (and variance) of organisms (**λ)**.

	Number of Trials		
λ	**2**	**3**	**5**
1	100.00%	100.00%	100.00%
2	99.99%	99.99%	99.98%
3	99.78%	99.67%	99.45%
4	98.38%	97.58%	96.00%
5	93.74%	90.75%	85.07%
6	83.92%	76.88%	64.51%
7	68.97%	57.28%	39.51%
8	51.36%	36.80%	18.90%
9	34.50%	20.27%	6.99%
10	20.97%	9.60%	2.01%
11	11.59%	3.95%	0.46%
12	5.88%	1.42%	0.08%
13	2.75%	0.46%	0.01%
14	1.20%	0.13%	0.00%
15	0.49%	0.03%	0.00%
16	0.19%	0.01%	0.00%
17	0.07%	0.00%	0.00%
18	0.02%	0.00%	0.00%
19	0.01%	0.00%	0.00%
20	0.00%	0.00%	0.00%

$\boldsymbol{\lambda}$ = the mean number of living organisms per volume (m^{-3} or mL^{-1}) and the variance. The row with 9 organisms per volume is highlighted, as it represents the cutoff point for individual tests meeting the discharge standard.

7.1.3.4 *Testing Alternate Filters—Criteria to Establish Equivalence among Filters*

Given that BWMS treatment efficacy and performance characteristics will be affected by filtration, one can ask what filter characteristics are the most important to evaluate under a standardized test? While a filter may be an interchangeable component, certain characteristics will be required to allow effective treatment and coordinated operations. At a top level, performance characteristics should be assessed through empirical testing, by comparing the results of the original filter used in TA to each of the alternate filters' results from the land-based challenge test. At a secondary level, equivalence between the original and alternate filters should be assessed by comparing their design and interface (with the BWMS) characteristics.

To assess equivalence, an initial list of criteria is provided in Table 11; note that additional criteria may be needed. For each item, data should be provided for the original filter used in TA testing and data should be provided for an alternate filter(s) tested according to the challenge conditions defined in the workshop. In this manner, the filters will be compared. Individual BWMS manufacturers should identify any additional characteristics that are required for successful use. Note that the intent of Table 11 is to identify characteristic performance data to be empirically examined and compared to alternate filters and the manufacturer's specifications to ensure functional and physical compatibility. Ideally, a test plan will also examine performance at minimum and maximum specifications to verify vendor claims; however, it is possible that in some cases, manufacturer limits may be outside the capabilities of a TF. Other requirements of testing, such as TF qualification, the number of replicate tests, and specific challenge conditions for given performance criteria will be defined by the workshop.

Performance characteristics include removal efficiency for a given size range of particles and organisms, as well as the operational flow and pressure ranges (Table 11). Logically, trading a filter with a larger pore size for one with a smaller pore size will increase treatment efficacy, but one drawback is that the filter likely will require more frequent cleaning (i.e., backflushing) during operation, which can affect the overall flow through the entire BWMS. Filter performance can also affect the pressure and water flow conditions provided to the downstream equipment. Thus, operational parameters can be affected by the type of filter (as well as the design of the self-cleaning apparatus). Design and interface characteristics include the type of filters, operational interfaces to the BWMS controls, mechanical design and construction, and maintenance requirements (Table 11). Many of the items listed are *not* commonly found in manufacturer's marketing information.

Table 11. Performance characteristics to establish equivalence among filters following empirical tests.

Performance Characteristics	
Empirical Tests of Filter Performance: Challenge Conditions	
Criterion	**Data Requirements**
Log and absolute removal of TSS	TSS before and after filter in challenge test
Log removal and absolute removal of organisms ≥50 µm	Organism counts before and after filter in challenge test
Log removal and absolute removal of organisms ≥10 and <50 µm	Organism counts before and after filter in challenge test
Empirical Tests of Filter Performance: Flow Ratings	
Criterion	**Data Requirements**
Rated minimum filter flow (m^3 h^{-1}, as identified by the BWMS vendor)	Operational performance characteristics at manufacturer specified minimum flow; the vendor would provide the data here, and it would be empirically tested
Rated maximum filter flow (clean filter; m^3 h^{-1})	Operational performance characteristics at manufacturer specified maximum flow under nominally low challenge load
Filter maximum operating pressure (psi)	Operational performance characteristics at manufacturer specified maximum operating pressure
Minimum inlet operating pressure (psi)	Operational performance characteristics at manufacturer specified minimum operating pressure
Differential pressure at maximum flow (clean filter; psi)	Differential pressure and flow characteristics under nominally low challenge load and maximum flow
Differential pressure set point to initiate cleaning cycle (psi)	Differential pressure and flow characteristics at onset of cleaning cycle as compared to the manufacturer's specification
Ability to control cleaning cycle via timer, if functionality is required by manufacturer	Functional test results and operational performance characteristics

psi = pounds per square inch, and TSS = total suspended solids.

7.1.3.5 Testing Alternate Filters—Test Documentation

Any testing on alternate filtration subsystems must address requirements for TA testing, and all variants of a BWMS with a manufacturer-defined filtration options must meet the requirements of 46 CFR 162.060. Any testing designed to demonstrate equivalency of filtration components must include an appropriate test plan (per §162.060-24), component testing (per §162.060-30), and test report (per §162.060-44). Such test documentation must clearly define the requisite characteristics necessary for equivalent performance of filtration subsystems within the overall

BWMS, including an acceptable range of test conditions specified for both CFD analysis and empirical testing.

7.2 Review of a Draft Proposal for Filter Testing

A filter manufacturer recently submitted a paper to USCG that describes component testing of filter subsystems independent of a BWMS to be performed by USCG approved Independent Laboratories (ILs). The approach considers USCG rules for testing a complete BWMS, and the paper describes several test conditions that need to be met during testing, such as testing at multiple salinities using organisms and TSS. The manufacturer suggests that a vendor can receive TA for interchangeable filter component subsystems when the performance of the tested filter proves equal to or better than a filter tested as part of the complete BWMS. Overall, the proposal is consistent with the land-based testing recommended in this report, but it is less detailed, lacking the minimum challenge conditions, data requirements for comparison, and the number of tests required for each salinity. For comparison, Table 12 lists the draft proposal and recommendations in this report. The discussion of additional details should be deferred to the expert workshop; such a workshop may benefit from a review of the draft proposal in conjunction with this report.

Table 12. Comparison of manufacturer's proposal and this report.

Manufacturer's Proposal	Proposal in this report	Are proposals similar?
Use USCG guidelines and protocol for ballast water testing as guide to filter testing at ILs with modifications	Use ETV Protocol approach "to verify a treatment system's performance using a set of challenging, but not rare, water quality conditions representative of the natural environment."; suggests completing this testing at land-based test facilities and convening an expert workshop to provide input to specific test parameters, methods, and analysis techniques	**Yes.** Both suggest testing at ILs using the current USCG and ETV approach. It is unclear if the manufacturer's proposal means testing should be conducted at land-based test facilities; however, the example data was generated at a land-based facility
95% or over biological removal efficiency organisms ≥50 µm	Data on the removal efficiency of organisms will be collected; data will expressed as both logarithmic reductions as well as numerical reductions; tests will be conducted with ambient assemblages (at ETV challenge conditions) of organisms, rather than STOs, given the field-scale approach needed	**Yes.** This report did not specify a removal efficiency number; this value would be measured during testing. The manufacturer's proposal did not specify the biological challenge conditions, but it appears the intent is to follow the ETV protocol
Comparing different removal rates in 3 salinities water sources (fresh, sea, and brackish water)	Consistent with US regulations, testing is recommended at all salinities in which the BWMS is approved for use	**No**. The manufacturer's proposal suggests 3 salinities, while this report allows for testing at fewer salinities
Test performed at the manufacturer's maximal declared filtration velocity, flow, and performance envelope	A manufacturer should list the filter's flow and the specification of the BWMS manufacturer. The flow rates should be expressed per unit volume (as per GSI's report), as it is easier for the end user to understand than per surface area of the filter	**No.** This report does not suggest testing at the manufacturer's maximum rated filtration flow. This may not be possible if a filter is rated for higher than the capacity of the TF, although such a test would provide verification data

Manufacturer's Proposal	Proposal in this report	Are proposals similar?
Testing should be done under a minimum load of 250 mg L^{-1} of TSS according to IL test protocol (that will contain a PSD of ≥60% of particles ≥50 µm)	Testing at ETV challenge conditions where data on TSS removal will be collected; the "Shanghai" test (high TSS loading) should be discussed in an expert workshop	**Yes**, **but** this report suggests starting with ETV challenge conditions and the possibility of adding a more challenging test (e.g., Shanghai) Also, the manufacturer's proposal is unclear if this load is TSS only or if it will also evaluate organism removal
Testing at maximum operating flow rate (filtration velocity with the nominal filtration degree)	Test flow are not specified, but this report does identify consideration of maximum (and minimum) flow in developing empirical test requirements	**No.** This report does not suggest testing at the maximum operating flow rate, and higher capacity filters may exceed the TF capabilities. This requirement should be discussed at an expert workshop
Minimum operating pressure ≤2 bars at inlet	Test pressures are not specified, but does identify consideration of maximum (and minimum) inlet pressure in developing empirical test requirements	**No.** The minimum operating pressure will be specific to the filter under test; it is unclear why this was pre-determined
Maximum allowed head loss at nominal flow (can be agreed as 3 or 5 m)	The minimum differential pressure across the (clean) filter and maximum differential pressure across the (dirty) filter are identified as empirical measurement criteria, as well as the set point at which filter cleaning is initiated (i.e., backflush)	**Yes, but** head loss or pressure differential depends on the type of filter being evaluated; the number specified by the manufacturer may not apply to all filters. Also, it was unclear if head loss referred to a clean filter or dirty filter; both are of interest
Vendor can receive approval for interchangeable filter components for the complete BWMS when the performance of the tested filter proves equal or better results in the above categories	The filter's BE and operational performance would be quantified, and alternate filters would be tested in the same manner to determine the alternate filters' equivalence to the original filter used in TA. After equivalence was established via challenge testing, the original TA certificate would be modified to incorporate the equivalent filters	**Yes.** Both proposals say the interchangeable filter must have test results equal to or better than the original filter

Manufacturer’s Proposal	Proposal in this report	Are proposals similar?
Not addressed: salinity	Suggests 3-5 tests for each salinity, consistent with the ETV	**No.** The number of tests needed at each salinity was not addressed in the manufacturer’s proposal.
Not addressed: test documentation	The following documentation is recommended: test plan (per §162.060-24), component testing (per §162.060-30), and test report (per §162.060-44)	**No.** Test documentation was not specified in the manufacturer’s proposal
O&M criteria	O&M testing is recommended, and that a workshop address the duration and specification of associated data	**No.** While testing of operational functions and monitoring of O&M parameters was indicated by the manufacturer, no O&M testing is required
Vendor specified system documentation to be assessed during testing	NRL identifies a set of performance characteristics and design and interface characteristics to be reviewed and assessed	**Yes**, and general criteria overlap, but a workshop would benefit from review of the manufacturer’s proposal criteria.

BE = biological efficacy, O&M = operations and maintenance, ETV = Environmental Technology Verification Program (Protocol), PSD = Particle size distribution, STO = standard test organisms, and TA = type approval.

8 CONCLUSIONS

Given that BWMS manufacturers want to specify multiple filter subsystems for use in their equipment, there are options for approving the use of alternate filters. The most highly recommended option is to maintain the default approach wherein each BWMS undergoes TA testing with a single filter, and if an additional filter is specified, an additional, full complement of land-based, shipboard, O&M, and component tests would occur to obtain TA for the new configuration. This approach would lend the most confidence in using the alternate filter, but it requires a substantive investment of time and money to complete requisite testing and is extremely unlikely to be practicable

A second approach is to conduct a full suite of TA testing on a BWMS with a “base filter” configuration. Then, a two- part approach would be followed: (1) A design study, and (2) A reduced number of BE tests of the alternate filter as installed in the BWMS would be conducted at an IL. This effort, however, would be reduced relative to that of full TA testing. Here, three land-based tests would be conducted, and O&M and component testing would also occur. Developing a comparison metric, such as the beta ratio or MERV rating used in other industries, would be exceptionally useful for stakeholders that might want to interchange different ballast water filters in BWMS, because it would accurately compare filters without having to rely only on the nominal rating as currently supplied by vendors of filters.

If time or practicality does not allow the above scenarios to be implemented, a third option is available, although it is not recommended at this time. In this scenario, a design study would be completed, followed by testing to demonstrate equivalence of an alternate filter with the original filter. Here, a series of land-based performance tests would be conducted on the filter itself (not installed in the BWMS). Such performance testing would require the same rigor as US TA testing with respect to the quality assurance, testing protocol, and data reporting. A test protocol would be developed following a process similar to that used for the ETV Protocol for land-based and shipboard testing of BWMS, that is, by convening panels of experts. This approach could be shown to be as effective as the first approaches, so it should be developed.

9 ACKNOWLEDGEMENTS

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Appendix A. SUMMARY OF COMMON FILTER RATINGS AND FILTER TESTS AS DESCRIBED IN FILTERS AND FILTRATION HANDBOOK (DICKINSON 1997)

Table 13. Filter ratings and filter tests.

Filter Rating or Test	Description
Absolute rating	Specifies particle size for 100% retention; no particle larger than the absolute rating will pass; this also means that all pores are equal to or smaller than the particle size and that 100% particles greater than the filter rating will be retained
Nominal rating	An arbitrary rating determined by the filter manufacturer to represent the degree of filtration. The rating depends on the type of test used to rate the filter; this is often not identified and the tests between manufacturers may not be the same
Mean filter rating	Mean pore size of the filter element
Beta ratio	A rating system that incorporates multi-pass testing to provide the filter manufacturer and the filter user an accurate and representative means for comparing between types of filter media
Filter efficiency	The efficiency at which the filter removes particles expressed as a percentage. This can be derived by subtracting the beta ratio from 1 and multiplying by 100. Often a range of particles is used; the glass bead test is the classic method for rating filter efficiency
Microbial rating with Log Reduction Value (LRV)	Most often used for membrane filters, this is defined as the logarithm of the ratio of total microorganisms in the challenge water to the microorganisms in the filtered fluid; test organisms are often *Pseudomonas diminuta*, but there is no international standard for the challenge bacteria
Filter permeability	The reciprocal of resistance to flow caused by the filter. High permeability means low resistance, and low permeability equals high resistance. The permeability coefficient (α) is related to the pressure drop at a given flow rate.
Effect of pulsating flow	Compares the number of particles loosened on a filter when subjected to agitation or pulsating flow; this rating is often higher than ratings achieved in a laboratory under steady state flow conditions.

Glass bead test	Measures concentration of sized glass beads before and after a filter; the largest bead size passed establishes the "absolute cut-off" rating for the filter. Data are presented as a histogram of particle size passing the filter; nominal rating is the bead size at which a certain percentage of glass beads passed (usually between 10% and 2%)
Mean particle passed test	Determines the size of the largest hard, spherical particle passing a filter. A measured quantity of artificial contaminant (normally glass beads from 2 to 80 µm in diameter) is introduced in a mixing chamber and delivered to the test unit; the diameter of the largest bead found in the filtrate is measured with a microscope and determines the absolute rating of the filter
Degree of filtration test	Similar to the glass bead test, where instead the weight of contaminant introduced and the weight of contaminant in filtrate are measured (rather than counting beads). The degree of filtration is the percentage of contaminant retained on the filter (W_1-W_2/W_1 x 100%); this test may be used to determine the nominal rating of the filter relative to a specific contaminant
Multi-pass test	Used to establish Beta ratio of hydraulic and lubrication filters. Medium-sized test dust (ISO #) is added to the test fluid, with particles counted upstream and downstream; beta ratio is determined by dividing particles upstream by particles downstream, and efficiency rating calculated from an equation
Single pass test	Contaminated fluid is introduced to the filter under test; effluent is collected in separate reservoir; particle counts upstream and downstream determine the removal efficiency of the filter
Bubble point test	For a given fluid and pore size and constant wetting, the pressure required to force an air bubble through the pore is inversely proportional to the size of the hole. Pore size is established by wetting the element with the fluid and measuring the pressure at which the first stream of bubbles is emitted from the upper surface of the element when air pressure is applied to the underside. The first stream of bubbles establishes the largest hole (path of least resistance). As pressure increases, air bubbles will appear over the entire element. This point is known as the open bubble point or 'boil' point the corresponding pressure at which this occurs identifies the mean pore size of the element. An equation based on Poiseuille's law is used to determine this pore size; the method applies primarily to membrane filters
Dirt capacity test	Developed for air filters or filters that are not self-cleaning
Pressure drop test	Measures the differential pressure (DP) across a filter (or filter element) when clean fluid is circulated at measured flow rates and temperatures

Collapse test	Measures the point at which filter collapse or failure occurs due to DP when contaminated fluid is processed at the flow rating of the filter
Media migration test	A performance test common for sand or other media filters; not applicable to BW filters
Fatigue tests	Subjects a filter to stop-start cycles or cycles of pressure fluctuation to determine integrity of filters; a bubble test is applied before and after the fatigue test to measure any changes in pore
Bacterial challenge test	Measures capacity of high efficiency filters to capture bacterial spores; does not apply to ballast water filters
Membrane cell test	Measures performance of reverse osmosis filters, nanofiltration and ultrafiltration; likely does not apply to ballast water filters

Appendix B. APPLICATIONS FOR ALTERNATE MANAGEMENT SYSTEM (AMS) DESIGNATION THAT SPECIFIED MULTIPLE FILTERS

Table 14. Alternate Management Systems (AMSs) specifying multiple filters.

BWMS	Filter 1	Filter 2	Filter 3	Filter 4
Alfa Laval PureBallast 2.0 and 3.0	Hydac RF10	Boll & Kirch 6.18.3	N/A	N/A
Auramarine Crystal Ballast	Boll & Kirch**	FilterSafe BSF-100H	N/A	N/A
BIO-UV, BIO-SEA	FilterSafe BS	Filtrex ACB	N/A	N/A
Cathelco Ltd **Cathelco BWMS**	Filtrex RFCA-22	Hydac ACB-935-200-C	N/A	N/A
Erma First **Erma First BWTS**	Bernoulli**	Krone**	Livic	N/A
Hyde Guardian	Arkal SpinKlin, Amiad Omega	Filtrex ACB	Hydac RF10	FilterSafe BallastSafe
OceanSaver AS OceanSaver MK II	Boll & Kirch*	FilterSafe BSFc-H-16	N/A	N/A
Optimarin AS	BallastSafe BSFc-H-16	Filtrex ACB	Boll 6.18.2	N/A
Qungdao Headway OceanGuard II	OceanGuard HMT		N/A	N/A
Samsung Purimar II	Hydac** (model not specified)	Samsung**	N/A	N/A
Sunruit Balclor	Boll 6.18.2	E.L.I AF-9800	FilterSafe**	Luoyang Sunrui**

*Strikethrough text indicates that filter was not listed on the type approval certificate, but other sources indicated this filter was used. ** Model not specified. N/A = not applicable.

Appendix C. REVIEW OF RELEVANT ISO STANDARDS

- ISO 565 specifies the nominal sizes of openings in a table for metal wire cloth with square openings, perforated metal plate, and electroformed sheet with square or circular openings (ISO 1990).

- ISO 3310 specifies three tests that are conducted when evaluating metal wire cloth, perforated metal plate, and electroformed sheets (ISO 2000). When evaluating wire cloth (which is most similar to ballast water screen material), several parts of the weave are defined (see Figure 7), where

    - *w* is the aperture size
    - *d* is the wire diameter
    - *p* is the pitch (w+d)

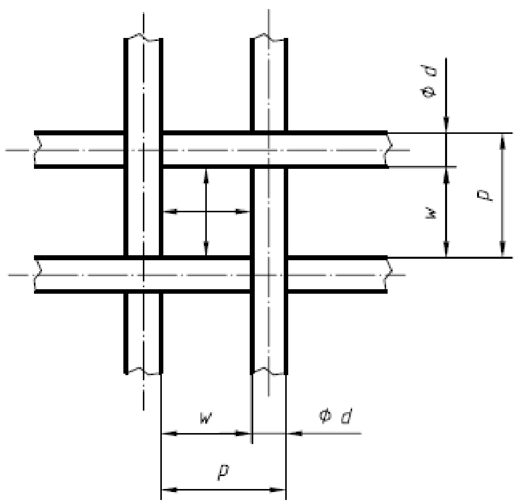

Figure 7. Aperture size (from ISO 2000). *d* = wire diameter, *w* = aperture size, and *p* = pitch (w+d)

A set of three specific tolerance and measurement methods are defined in this standard for all of the variables shown in Figure 7. Also considered are warp (wires in the horizontal direction) and weft (wires in the vertical direction). First, the mesh is given a general inspection, which is a visual examination in which the cloth is viewed with an illuminated background, and any issues with uniformity of appearance, defects, wrinkles, etc. are examined. If found, the sieve is unacceptable. Second, the apertures are methodically inspected using magnification to look for areas of the mesh that may be oversized. Third, the individual apertures are spot checked and measured in the warp and weft directions, diagonal directions, or all full apertures in a field of view on the microscope. The total number of apertures needed to be measured for compliance to the standard is listed in a table within the standard. The average aperture size, the standard deviation, and the wire diameter must all comply with values in a table in the standard, or the sieve is unacceptable.

- ISO 14351 defines testing requirements for industrial wire screens (rather than metal cloth; ISO 1997). The standard is designed for industrial screening processes, but it does not mention using these screens in water. The beginning of this standard defines the aperture width following Figure 7 above. The open screening area is also defined using the following equation:

$$A_O = \frac{w^2}{(w+d)^2}$$

Also discussed is the mass per unit area, which has the following equation:

$$\rho_A = \frac{d^2 \rho f}{618.1(w+d)}$$

Where

- f is the type conversion factor (see ISO 4783-1:1989, table 2)
- ρ is the material density in kg m^{-3}

The standard has requirements on tolerances for wire diameter, aperture width, average aperture size, maximum aperture size, permissible number of major blemishes from manufacturing, flatness of wire screens, and surface conditions. There is also discussion on the types of wire used in wire screens (high-tensile steel, stainless steel, other weavable metals) although this may not apply for materials used in seawater. The standard describes test methods for measuring the wire diameter, aperture width, average aperture size, maximum aperture size, and it requires a set of inspection documents that state that the wire screen complies with this ISO standard. There was no description of a test using beads, air bubbles, or another method for evaluating the screen.

Appendix D. MINIMUM EFFICIENCY REPORTING VALUE TABLE

Table 15. ASHRAE guidance on minimum efficiency reporting value (MERV) used for comparing filter effectiveness for different residential air filters (Table from EPA 2014, http://www.epa.gov/iaq/pubs/residair.html#Types-of-Particle-Removal-Air-Filters).

ASHRAE Standard 52.2				**ASHRAE Standard 52.1**	**Application Guidelines**		
MERV	**Particle Size Removal Efficiency, Percent in Particle Size Range, µm**			**Dust-Spot Efficiency Percent**	**Particle Size and Typical Controlled Contaminant**	**Typical Applications**	**Typical Air Filter/Cleaner Type**
	0.3 to 1	**1 to 3**	**3 to 10**				
20	≥99.999	in 0.1 - 0.2 µm particle size		-	**<0.3 µm** Virus (un attached) Carbon Dust Sea Salt All combustion smoke	Electronics manufacturing Pharmaceutical manufacturing Carcinogenic materials	HEPA/ULPA Filters*
19	≥99.999	in 0.3 µm particle size		-			
18	≥99.99	in 0.3 µm particle size		-			
17	≥99.97	in 0.3 µm particle size		-			
16	>95	>95	>95	-	**0.3-1 µm** All bacteria Droplet nuclei (sneeze) Cooking oil Most smoke Insecticide dust Most face powder Most paint pigments	Superior commercial buildings Hospital inpatient care General surgery	**Bag Filters** - Non supported (flexible) microfine fiberglass or synthetic media, 12 to 36 inches deep. **Box filters** - Rigid style cartridge, 6 to 12 inches deep.
15	85-95	>90	>90	>95			
14	75-85	>90	>90	90-95			
13	75	>90	>90	80-90			

ASHRAE Standard 52.2				ASHRAE Standard 52.1	Application Guidelines		
MERV	**Particle Size Removal Efficiency, Percent in Particle Size Range, µm**			**Dust-Spot Efficiency Percent**	**Particle Size and Typical Controlled Contaminant**	**Typical Applications**	**Typical Air Filter/Cleaner Type**
	0.3 to 1	**1 to 3**	**3 to 10**				
12	-	>80	>90	70-75	**1-3 µm** *Legionella* sp. Humidifier dust Lead dust Milled Flour Auto emission particles Nebulizer drops	Superior residential Better commercial buildings Hospital laboratories	**Pleated filters** - Extended surface with cotton or polyester media or both, 1 to 6 inches thick. **Box Filters** - Rigid style cartridge, 6 to 12 inches deep.
11	-	65-80	>85	60-65			
10	-	50-65	>85	50-55			
9	-	<50	>85	40-45			
8	-	-	>70	30-35	**3-10 µm** Mold Spores Dust mite body parts and droppings Cat and dog dander Hair spray Fabric protector Dusting aids Pudding mix	Better residential Commercial buildings Industrial workspaces	**Pleated filters** - Extended surface with cotton or polyester media or both, 1 to 6 inches thick **Cartridge filters** - Viscous cube or pocket filters **Throwaway** - Synthetic media panel filters
7	-	-	50-70	25-30			
6**	-	-	35-50	<20			
5	-	-	20-35	<20			

ASHRAE Standard 52.2				ASHRAE Standard 52.1	Application Guidelines		
MERV	**Particle Size Removal Efficiency, Percent in Particle Size Range, µm**			**Dust-Spot Efficiency Percent**	**Particle Size and Typical Controlled Contaminant**	**Typical Applications**	**Typical Air Filter/Cleaner Type**
	0.3 to 1	**1 to 3**	**3 to 10**				
4	-	-	<20	<20	**> 10 µm** Pollen Dust mites Cockroach body parts and droppings Spanish moss Sanding dust Spray paint dust Textile fibers Carpet fibers	Minimum filtration Residential window air conditioners	**Throwaway** - Fiberglass or synthetic media panel, 1 inch thick **Washable** - Aluminum mesh, foam rubber panel **Electrostatic** - Self-charging (passive) woven polycarbonate panel
3	-	-	<20	<20			
2	-	-	<20	<20			
1	-	-	<20	<20			

* The last four MERV values of 17 to 20 are not part of the official standard test, but they have been added by ASHRAE for comparison purposes. Ultra Low Penetration Air Filters (ULPA) have a minimum efficiency of 99.999% in removing 0.3 µm particles, based on the IEST test method. MERVs between 17 and 19 are rated for 0.3 µm particles, whereas a MERV of 20 is rated for 0.1 to 0.2 µm particles. ** For residential applications, the ANSI/ASHRAE Standard 62.2-2007 requires a filter with a designated minimum efficiency of MERV 6 or better.

Appendix E. MATHEMATICAL MODEL OF THE NUMBER OF BIOLOGICAL EFFICACY TESTS

A critical parameter in testing is how varying the number of independent trial replications would affect likelihood of obtaining a successful test result. To this end, the probabilities of known organism densities were examined in order to establish and compare how varying the number of trial replications affects the final test result, which, by necessity, is defined in binary terms as either a success or a failure.

To calculate the probabilities of successful tests, the components of the probability calculations and the criteria for success ("passing") and failure are established as:

1. Let n be the number of independent trials performed, and
2. Define the random variables X_i as the number of organisms in the sample in trial *i* (*i* = 1, 2, …, n).

Noting that no more than nine organisms can be found in a given sample in order for it to be considered a passing trial, and given the independence of each of the n trials:

$$P(Passing\ Test) = P(X_1 \leq 9\ \cap X_2 \leq 9 \cap \ldots \cap X_n \leq 9) = \prod_{i=1}^{n} P(X_i \leq 9) \tag{1}$$

Also, note that in the event that each of the independent trials is performed under circumstances where they are sampling from the same distribution, then:

$$P(X_1 \leq 9) = P(X_2 \leq 9) = \cdots = P(X_n \leq 9) \tag{2}$$

Thus, the product of the probabilities simply equals the probability of any one of the equivalent X_i probabilities to the nth power:

$$\prod_{i=1}^{n} P(X_i \leq 9) = P(X_1 \leq 9)^n \tag{3}$$

Now, assuming that X_i is Poisson distributed ($X_i \sim Poisson(\lambda)$, where parameter λ is the mean and variance; in this case, the mean density of organisms present in the sampled water, either m^{-3} or mL^{-1}) and therefore has the following probability mass function (PMF):

$$P(X = x) = \frac{e^{-\lambda}\lambda^x}{x!}\ I_{\{0,1,2,\ldots\}}(x) \tag{4}$$

A visual of the PMF at varying values of λ is shown in Figure 8. Note that as the Poisson distribution is discrete, the function is defined only at integer values on the horizontal axis. The

lines are present only as a visual aid. As the parameter λ increases, the curve more closely approximates a normal distribution.

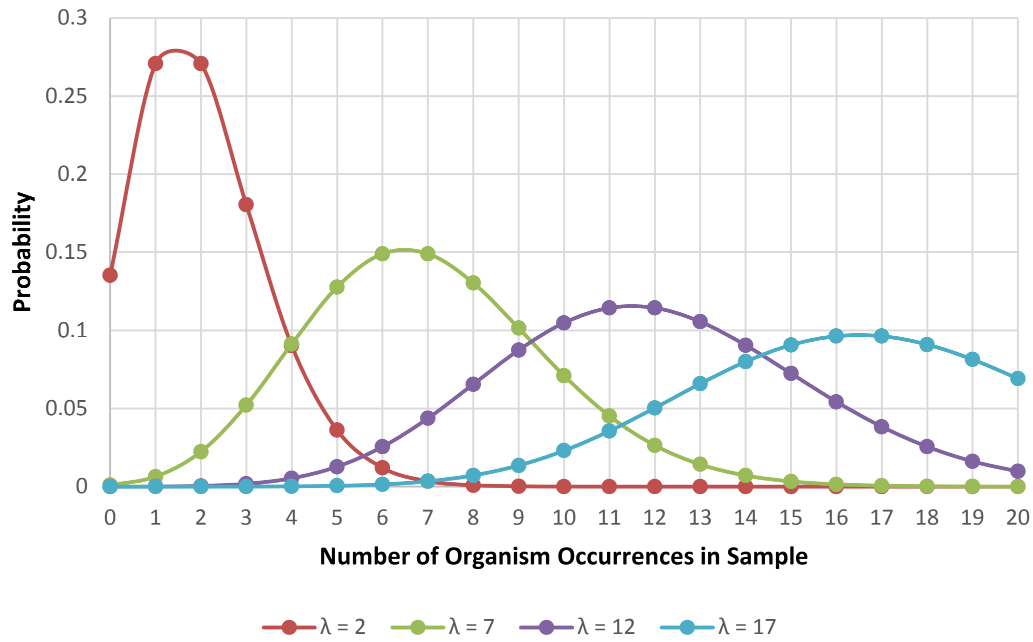

Figure 8. Probability mass function of the Poisson distribution. P = probablility.